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RELATIVE EVALUATION OF CANDIDATE LONGITUDINAL FLYING QUALITIES CRITERIA APPLICABLE TO FLARED LANDING AND APPROACH

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The purpose of this study was to determine which of the flying qualities criteria recommended in the proposed MIL-PRIME Standard and Handbook (reference a) provided the best method to predict the short period longitudinal handling qualities levels for the approach and flared landing tasks for transport aircraft. The requirements listed in the Handbook were applied to the dynamic configurations and associated pilot ratings provided ~~by Calspan~~ in their Flared Landing Approach Flying Qualities Study for NASA/Langley documented in NASA CR 178188. Various equivalent system techniques were applied in this study, but none could generate equivalent transfer functions which satisfactorily correlated with the pilot ratings. ~~A much~~ simpler and less time consuming criteria was the transient peak ratio, rise time, effective delay criteria. This technique provided the same results as the "best" equivalent system match. The gain attenuation and phase rate criterion from the Dropback and Nichols chart criterion provided the best correlation with the pilot evaluations in predicting Level 1 and non-Level 1 configurations. More research is necessary to determine boundaries for the handling qualities levels. The time domain criterion, from the alternate criteria proposed in the NASA study, showed very good results but seemed highly dependent on aircraft type and task. Also, as a result of the study, potential boundaries were found for the pilot phase and gain values used in the closed-loop criterion.

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b	wing span, ft
$\bar{c}$	mean aerodynamic chord, ft
C_L	lift coefficient = $L/\bar{q}S$
C_{L_α}	$\partial C_L/\partial\alpha$
dB	decibel units for Bode amplitude = $20 \log_{10}$ (amplitude)
F_s	elevator wheel force, positive aft, lb
g	gravitation constant = 32.17 ft/sec^2
Ixx, Iyy, Izz	moments of inertia about x, y, z body axes, slug-ft^2
Ixz	product of inertia x, z body axes, slug-ft^2
Kc	command gain, deg/lb
Kp	pilot gain for closed-loop criterion
L	total lift, lb
m	mass of airplane, slugs
ms	milliseconds
n_z	normal acceleration, positive up, g's
$n_{z_{cg}}$	normal acceleration at the c.g.
n_{z_p}	normal acceleration at the pilot station
q	pitch rate, deg/sec
$\bar{q}$	dynamic pressure = $1/2\ \rho V^2$, lb/ft
s	Laplace operator, sec
S	reference wing area, ft^2
t_1	effective time delay from maximum slope intercept method, sec
$1/T_{\theta_2} \approx L_\alpha$	$\dfrac{g\ C_{L_\alpha}}{V\ C_L}$
Δt	rise time from time history criteria analysis, sec

LIST OF SYMBOLS (Continued)

V	airspeed, ft/sec
Xmp	distance along X-body axis between the c.g. and pilot station, ft
Yc	θ/F_s or θ/δ transfer function of aircraft and its control system
Yp	analytical pilot model
α	angle of attack, deg
γ	flight path angle, deg
Δn_z	incremental normal acceleration, g's
δ_e	elevator surface deflection, positive T.E. down, deg
ζ	damping ratio
ζ_{PH}	damping ratio of the phugoid mode
ζ_{sp}	damping ratio of the short period mode
θ	pitch attitude, deg
ρ	air density, slug/ft^3
τ_{n_z}	normal acceleration rise time, sec
τ_{P1}	numerator time constant for pilot model, sec
τ_{P2}	denominator time constant for pilot model, sec
τ_o	time delay, sec
Φ	phase angle of frequency response, deg
ω	frequency, rad/sec or Hz
ω_{bw}	bandwidth frequency, rad/sec
ω_{PH}	undamped natural frequency of the phugoid mode, rad/sec
ω_{sp}	undamped natural frequency of the short period mode, rad/sec

AUTHOR'S NOTE

The analysis done in this report was based on the short period flying qualities criteria recommended in the proposed MIL-PRIME Standard and Handbook. Between the time of this study (Aug '87) and its publication (Dec '87) the MIL-PRIME Standard and Handbook has received the official designation of MIL-STD 1797. In reference to the work done in this study, there is little difference between what was written in the Handbook and what is now Appendix A of MIL-STD 1797. Therefore, the results, conclusions and recommendations stated in this study are also applicable to MIL-STD 1797.

1.0 INTRODUCTION

1.1 BACKGROUND

The MIL-PRIME Standard and Handbook, (reference a) was designed so that a custom MIL-Standard will be developed for each new procurement or major modification of an existing aircraft. The procedure used to develop a Standard is to identify mission requirements, break down the mission requirements to mission tasks and select the most appropriate handling qualities criteria from the Handbook and insert it into the Standard. For the short period response, the Requirement Guidance Section of the Handbook lists six alternate criteria. They are as follows:

1. CAP or $\omega_{sp}^2/(n/\alpha)$, ζ_{sp}, τ_o
2. $\omega_{sp}T_{\theta_2}$, ζ_{sp}, τ_o
3. Transient Peak Ratio, Rise Time, Effective Delay
4. Bandwidth, Time Delay
5. Closed Loop Criteria
6. Dropback and Nichols Chart Boundaries

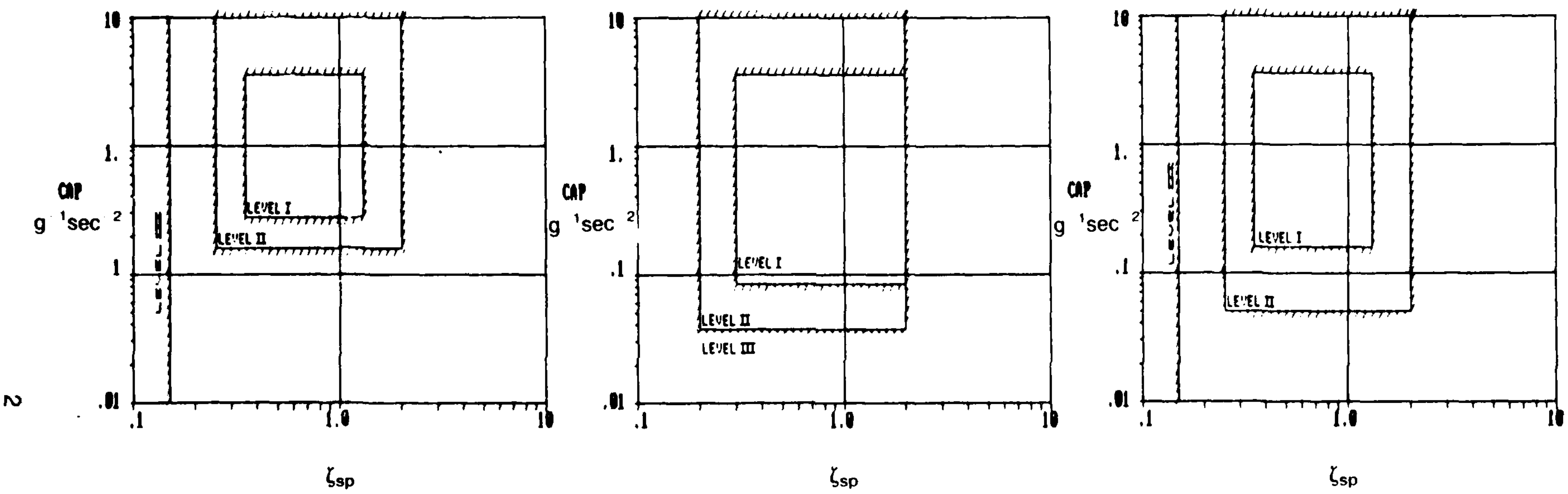
The first criterion listed above is based on the ω_{sp} vs n/α boundaries from MIL-F-8785C (reference c). CAP or Control Anticipation Parameter is defined as the ratio of the initial angular acceleration in pitch to the steady state change in load factor for a longitudinal step input. CAP is equivalent to $\omega_{sp}^2/(n/\alpha)$ with $n/\alpha = (V/g)\,(1/T_{\theta_2})$. The corresponding CAP boundaries for Categories A, B and C are shown in Figure 1. The second criteria uses the product of $\omega_{sp}T_{\theta_2}$ as a metric instead of the CAP values. The product $\omega_{sp}T_{\theta_2}$ measures the lag in phase at ω_{sp} or rather the time between the attitude and flight path responses to elevator deflection. Figure 2 shows the Category A, B and C boundaries for $\omega_{sp}T_{\theta_2}$ vs ζ_{sp}. It is still unresolved as to which metric is better, generally the product $\omega_{sp}T_{\theta_2}$ correlates well with documented CAP results. There are cases where $\omega_{sp}\,T_{\theta_2}$ provided slightly better results than using the CAP values (reference a).

The Handbook requires simultaneous equivalent system matches with the pitch and normal load factor at the center of rotation transfer functions for these two criteria. The resulting equivalent transfer functions have the following forms:

$$\frac{q}{F_s} = \frac{Kq\,(s + 1/T_{\theta_2})\,e^{-\tau_o s}}{s^2 + 2\,\zeta\,\omega_{sp}\,s + \omega_{sp}^2}$$

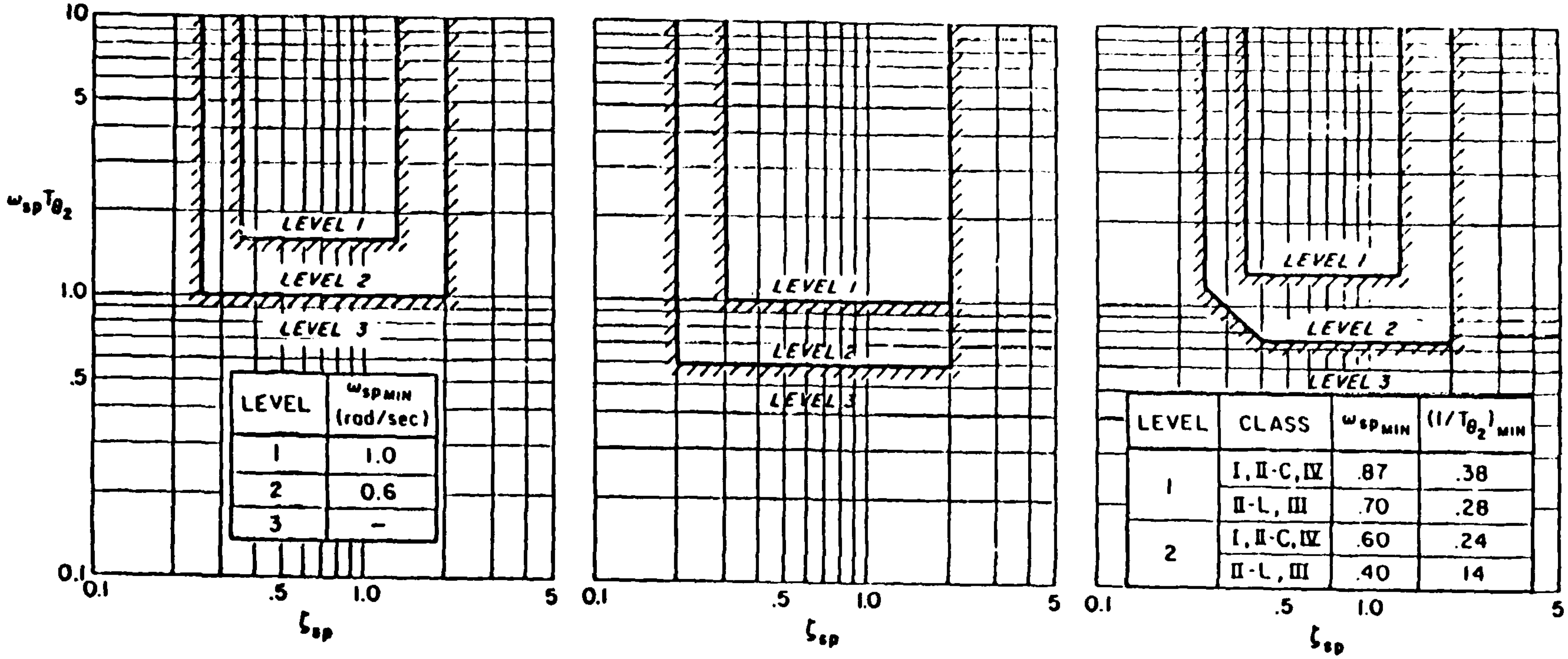
$$\frac{n_z}{F_s} = \frac{Kn\,e^{-\tau_o s}}{s^2 + 2\,\zeta\,\omega_{sp}\,s + \omega_{sp}^2}$$

over a frequency range of 0.1 to 10.0 rad/sec.



a) Category A   b) Category B   c) Category C

FIGURE 1 SHORT PERIOD DYNAMIC REQUIREMENTS
(Reference a)



a) Category A

b) Category B

c) Category C

FIGURE 2 REQUIREMENTS FOR SHORT-TERM PITCH RESPONSE TO PITCH CONTROLLER ($\omega_{sp}T_{\theta_2}$ vs. ζ_{sp})

(Reference a)

The transient peak ratio, rise time, effective delay criterion is effectively a short period pitch rate time history criterion. Figure 3 defines the quantities in this criterion. The pitch rate response is that to a step input of controller force or deflection calculated from the two-degree-of-freedom equations of motion. The benefit of this criterion is that an equivalent system match is not necessary and it is not limited by the order of the transfer function.

The effective rise time, Δt, was derived from the CAP limits defined in MIL-F-8785C. The Handbook gives maximum and minimum Δt values for the terminal and nonterminal flight phases — corresponding to Category C and B requirements. For example, Level 1 CAP requirements for Category C flight phase were:

$$.16 \leq \omega_{sp}^2 / (n/\alpha) \leq 3.6 \text{ rad}/(g \, \alpha \, \sec^2)$$

which according to the Handbook can be related to the effective rise time by the following substitution:

$$.16 \leq g/V_t(\Delta t) \leq 3.6 \text{ rad}/(g \cdot \sec^2)$$

This can then be rearranged to produce the limits given in the Handbook —

$$g / (3.6\, V_t) \leq \Delta t \leq g / (.16 V_t) \text{ sec}$$

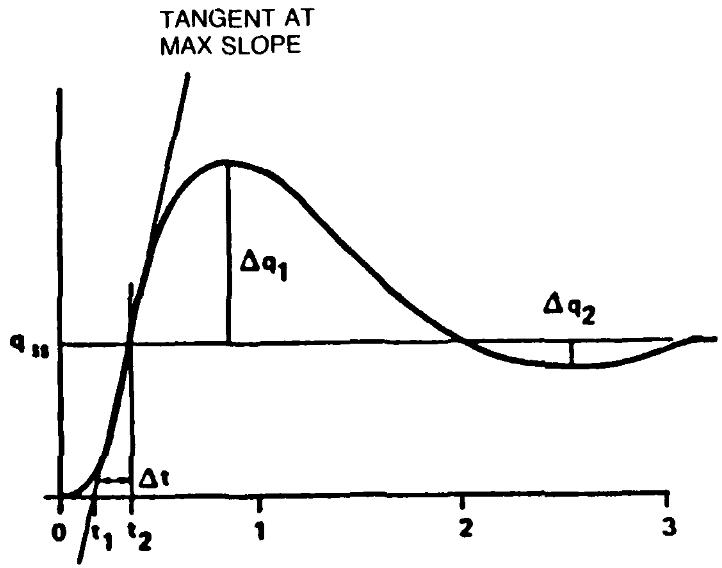
The maximum Δt values for Levels 1 and 2 of the nonterminal phase as well as the maximum Level 2 Δt value for the terminal phase of flight corresponds to relaxed CAP minimums. These values are a result of correlation with flight test data from existing aircraft (reference a).

The transient peak ratio, $\Delta q_2/\Delta q_1$, describes the damping of the system. The limits, as described in the Handbook, are based on the minimum damping requirements from MIL-F-8785C.

The bandwidth criterion is another criterion that could support higher order transfer functions, since it is based on the open-loop pitch attitude frequency response to pilot control force or deflection. The Handbook defines the bandwidth, ω_{bw}, as the highest frequency at which the phase margin is at least 45 degrees *and* the gain margin is at least 6 dB (Figure 4). The equivalent time delay is defined as:

$$\tau_p = -(\Phi_{2\omega_{180}} + 180)/(57.3 \times 2\omega_{180})$$

where ω_{180} is the frequency corresponding to -180 degrees of phase and $\Phi_{2\omega_{180}}$ is the phase angle at twice that frequency. Category A and C requirements are shown in Figure 5. Category B requirements were not given in the Handbook due to insufficient data.



Pitch rate response to step input of pitch controller force or deflection

$\frac{\Delta q_2}{\Delta q_1}$ ~ TRANSIENT PEAK RATIO

t_1 ~ EFFECTIVE TIME DELAY

Δt ~ EFFECTIVE RISE TIME $t_2 - t_1$

TRANSIENT PEAK RATIO, $\Delta q_2/\Delta q_1$

LEVEL	MAX $\Delta q_2/\Delta q_1$
1	$\leq .30$
2	$\leq .60$
3	$\leq .85$

EFFECTIVE TIME DELAY, t_1

LEVEL	t_1
1	$\leq .12$
2	$\leq .17$
3	$\leq .21$

EFFECTIVE RISE TIME, Δt

LEVEL	MIN	MAX
1	$9/V_t$	$200/V_t$
2	$3.2/V_t$	$645/V_t$

V_t = TRUE AIRSPEED ft/sec

FIGURE 3 TRANSIENT PEAK RATIO, RISE TIME, EFFECTIVE DELAY PARAMETERS

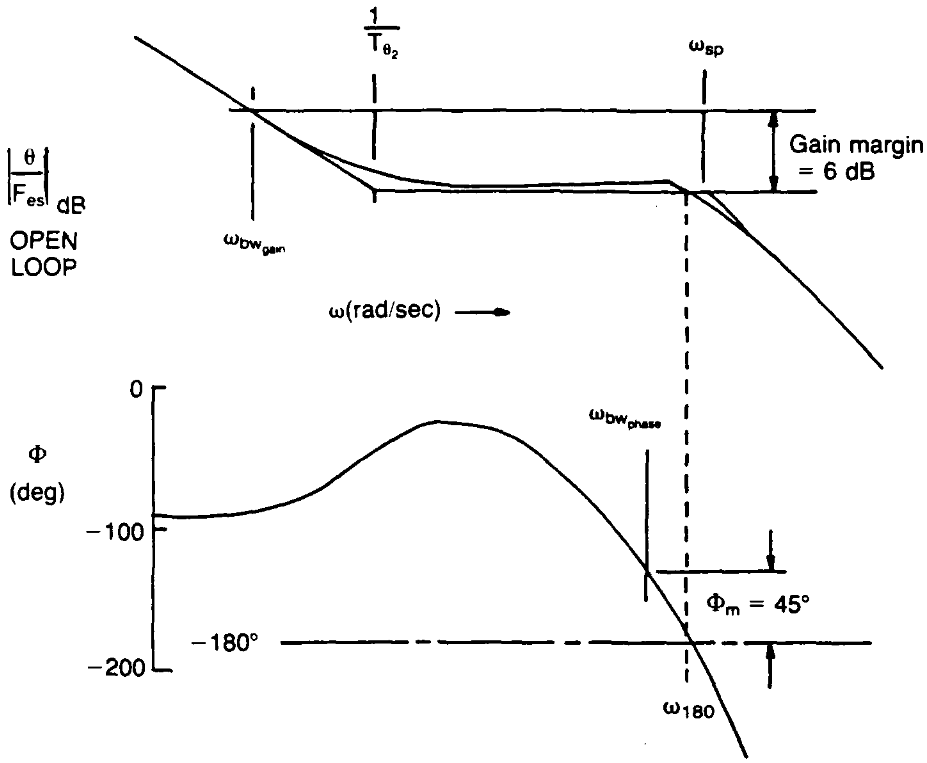
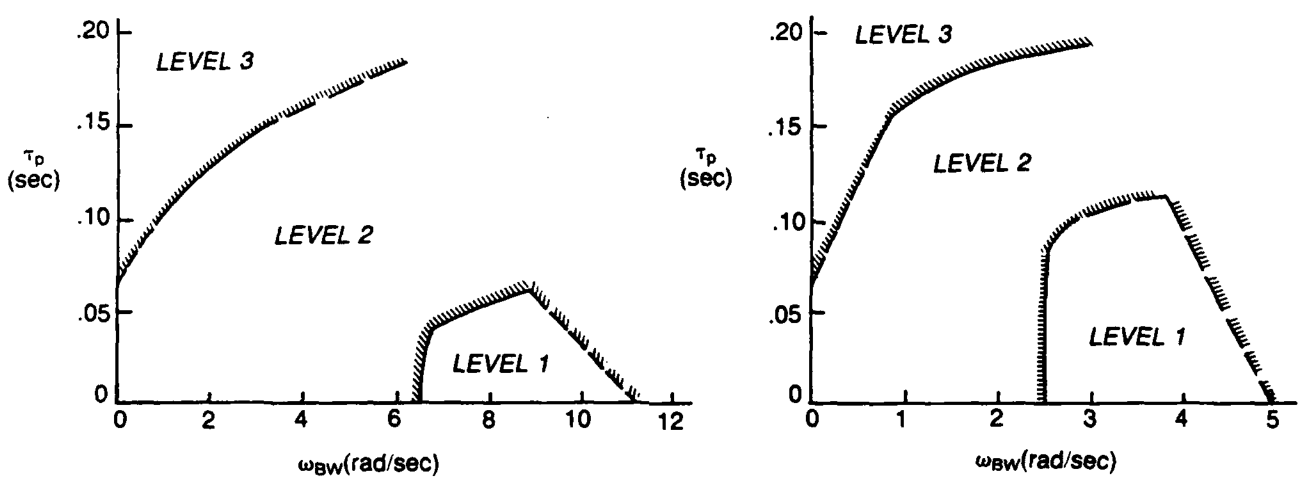


FIGURE 4 DEFINITION OF BANDWIDTH FREQUENCY, ω_{BW}, FROM OPEN LOOP FREQUENCY RESPONSE



a) Category A Flight Phases

b) Category C Flight Phases

FIGURE 5 BANDWIDTH REQUIREMENTS

The closed-loop criterion is based on a single-loop closure on pitch attitude based on the following Figure.

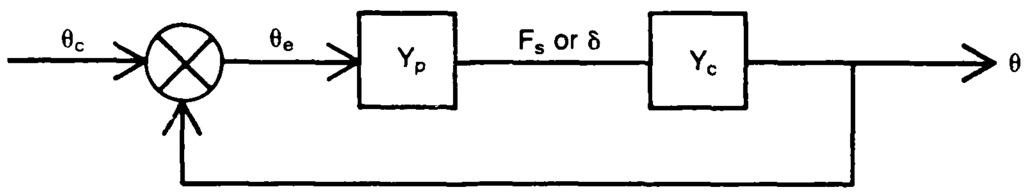


FIGURE 6 PILOT CONTROL LOOP FOR PITCH ATTITUDE

Y_c is the θ/F_s or θ/δ transfer function of the aircraft and flight control system where F_s is the pilot force and δ is the controller deflection. θ_c is an external pitch attitude command and θ_e is the pitch attitude error. Y_p is the analytical pilot model described as either

$$Y_p = Kpe^{-.25s}\frac{(\tau_{P1}\,s+1)}{(\tau_{P2}\,s+1)} \quad \text{or} \quad = Kpe^{-.25s}\,\frac{(5s+1)}{s}\,\frac{(\tau_{P1}\,s+1)}{(\tau_{P2}\,s+1)}$$

The Handbook recommends, for landing, a bandwidth of 2.5 rad/sec for a closed-loop phase of -90 degrees shall be attainable with closed-loop droop no more than -3 dB for Levels 1 and 2. Closed-loop resonance no greater than 3 dB for Level 1, 9 dB for Level 2 over the frequency range from 0 to 10 rad/sec. No constraints were given for the Kp, τ_{P1}, and τ_{P2} values of the pilot model. The magnitude and bandwidth requirements may apply to either the force or deflection control inputs.

The final recommended criterion presented in the Handbook was derived from the guidelines developed by Gibson (references d and e). Level 1, 2, or 3 boundaries are not defined since this criterion was mainly intended for fly-by-wire control law optimization. The criterion consists of four parts for Category C flight. First, a pitch rate time history is required to determine the attitude dropback as defined in Figure 7. It normally should be negative. Second, the normalized n_z step step response for n_z at the c.g. should fall within the envelope shown in Figure 8. The corresponding rise time, τ_{n_z}, should be within the boundaries shown in Figure 9. Third, the frequency response of the θ/F_s transfer should fall within the envelope shown in Figure 10 with the gains of the θ/F_s transfer function adjusted so that the crossover is at -120 degrees of phase. The frequency at -120 degrees of phase is to be between 0.25 and 0.5 Hz. Lastly, in addition to conforming to the requirements for the frequency response envelope, the θ/F_s frequency response must satisfy the gain attenuation to be greater than 0.1 deg/lb at -180 degrees of phase and that the phase rate must be greater than 100 deg/Hz at -180 degrees of phase.

This background indicates that much work has been done in an attempt to develop a general short period requirement but no one criterion has always been applicable. The Handbook gives first preference to CAP or $\omega_{sp}^2/(n/\alpha)$, ζ_{sp}, τ_o requirement from MIL-F-8785C using the equivalent systems technique. For those highly augmented aircraft where a "good" equivalent system match is not possible, the other criteria may be applied at the discretion of the procuring agency.

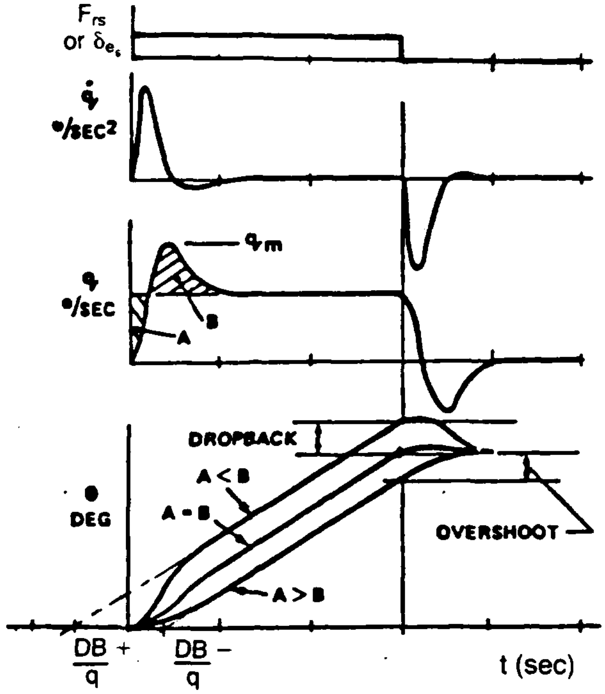


FIGURE 7 PITCH SHORT PERIOD TIME RESPONSES
(Reference d)

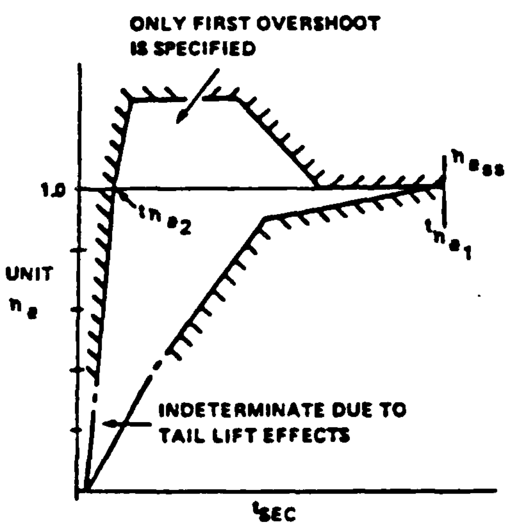


FIGURE 8 NORMALIZED n_z RESPONSE ENVELOPE
(Reference d)

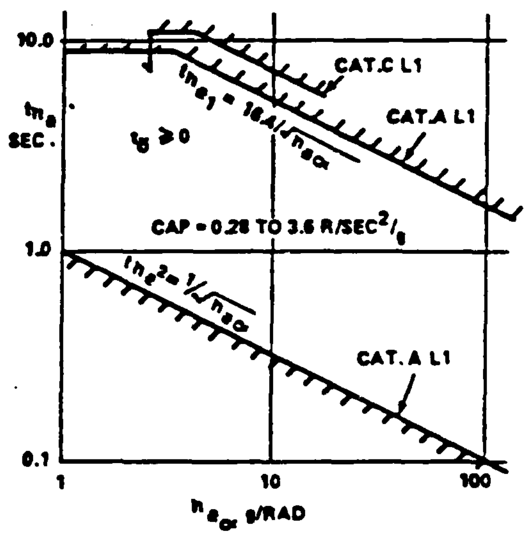


FIGURE 9 τ_{n_z} vs. n/α
(Reference d)

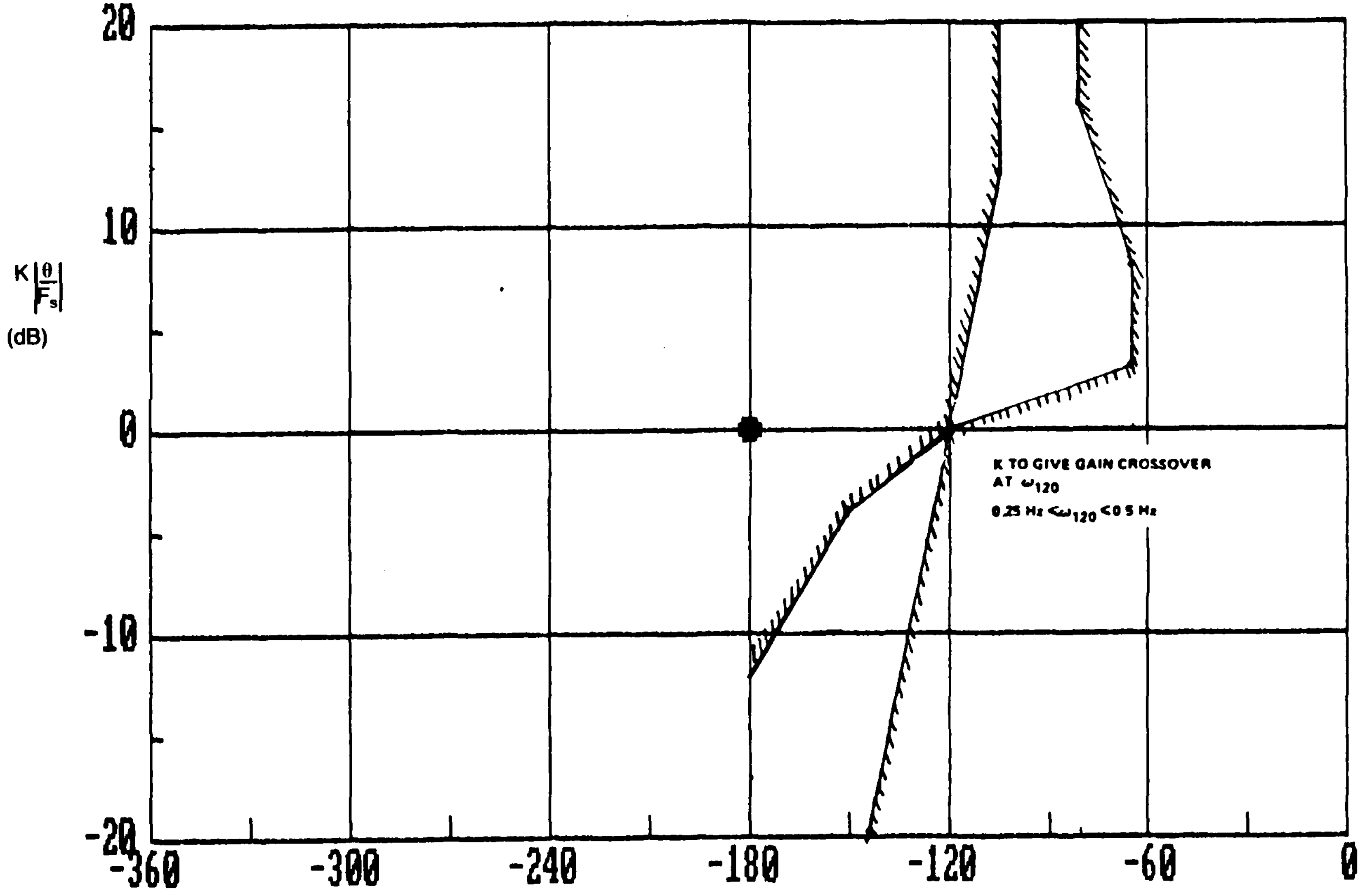


FIGURE 10 SATISFACTORY RESPONSE ENVELOPE — APPROACH AND LANDING

(Reference d)

The Flight Dynamics Branch of the Naval Air Development Center, as part of its effort to identify flying qualities criteria for manned aircraft, undertook the investigation of the short period requirements recommended in the Handbook. This was done to determine which of the criteria would be most appropriate for present and future Navy transport in the approach and flared landing tasks. The requirements listed in the Handbook were applied to the dynamic configurations listed in reference b. The predicted flying qualities levels were then compared with the associated pilot ratings.

1.2 PURPOSE

The purpose of this study was to consider several existing short period dynamic requirements for the approach and flared landing tasks in order to determine which of the criteria provided the best method to predict the handling qualities levels for a generic transport and use these results for the application in future Navy Standards for transport aircraft. This was accomplished using information from NASA Contractor Report 178188, "Flared Landing Approach Flying Qualities" (reference b); configurations 1 through 14 were considered as well as the baseline configuration. This report presents the various criteria applied and compares the predicted results with the associated pilot ratings.

1.3 SCOPE

The dynamic configurations used in this effort encompassed four classes of control command systems: angle of attack, pitch rate, angle of attack and pitch rate hybrids and flight path rate. For all the cases the short period frequency was kept constant at ω_{sp} = 2.0 rad/sec. The short period damping was varied as ζ_{sp} = 0.7, 1.3, 2.1 and $1/T_{\theta_2}$ was varied as $1/T_{\theta_2}$ = 0.5, 0.9, 2.0. The phugoid characteristics were varied to provide the appropriate command system by pole-zero placement. The values for ζ_{sp} and $1/T_{\theta_2}$ were chosen so as to potentially yield Level 1 through 3 handling qualities ratings based on MIL-F-8785C requirements. Table 1 lists the values for each configuration.

TABLE 1 CONFIGURATION CHARACTERISTICS

CONFIG. NO.	CONFIGURATION SHORT TERM RESPONSE	CONFIGURATION LONG TERM RESPONSE	SHORT PERIOD MODE	PHUGOID MODE	$1/T_{\theta_2}$
1	α_c	α_c	[.7, 2]	[.1, .3]	(.5)
2	q_c	q_c	(8)(.5) $\zeta \equiv 2.1$	(.1)(0)	(.5)
3	α_c	q_c	[.7, 2]	(.1)(0)	(.5)
4	q_c	α_c	(8)(.5) $\zeta \equiv 2.1$	[.1, .3]	(.5)
5	α_c	α_c	[.7, 2]	[.1, .1]	(.9)
6	q_c	q_c	(4.4)(.9) $\zeta \equiv 1.3$	(.1)(0)	(.9)
7	α_c	q_c	[.7, 2]	(.1)(0)	(.9)
8	q_c	α_c	(4.4)(.9) $\zeta \equiv 1.3$	[.1, .1]	(.9)
9	α_c	q_c, α_c	[.7, 2]	(.1)(0)	(.5)
10	q_c	q_c, α_c	(8)(.5) $\zeta \equiv 2.1$	(.1)(0)	(.5)
11	$\dot{\gamma}_c$	$\dot{\gamma}_c$	(2)	(0)(0)	(.5)
12	$\dot{\gamma}_c$	$\dot{\gamma}_c$	[.7, 2]	(0)(0)	(.5)
13	α_c	α_c	[.7, 2]	[.1, .3]	(2)
14	q_c	q_c	[1, 2]	(.1)(0)	(2)
B	α_c	α_c	[.7, 2]	[.095, .16]	(.75)

NOTE: $1/T_{\theta_1}$ = .1

$[\zeta, \omega] = s^2 + 2\zeta \omega_n s + \omega_n^2$

$(a) = s + a$

The short period criteria applied to the aircraft configurations were those recommended in the Handbook. Modifications of the Handbook criteria specifically meant for transport aircraft were also considered. In addition an angle of attack time history envelope and a time domain predictive criteria were included in this effort.

1.4 APPROACH

The approach taken in this study was to consider the configurations from reference b and sequentially apply the criteria recommended in the Handbook. In addition, two criteria mentioned in the flared landing study were also considered. They were an angle of attack time history envelope and a time domain predictive criterion.

As was mentioned in the background section, the Handbook requires simultaneous equivalent system matches with the pitch and normal load factor at the center of rotation transfer functions for the CAP and $\omega_{sp}T_{\theta_2}$ criteria. For this study the center of rotation was at the pilot station except for configuration 12 where the center of rotation was at the c.g. Also, if phugoid effects were present, the frequency range was reduced from 0.1 to 10.0 rad/sec to 0.3 to 10.0 rad/sec.

Taking into consideration that other equivalent system matching techniques could produce different "equivalent" results, several other techniques were considered. A second simultaneous match with q/F_s and n_z/F_s was determined with n_z at the center of gravity. Then an equivalent system match was determined using only the q/F_s transfer function and similarly an equivalent system match was determined using only the angle of attack to pilot stick force (α/F_s) transfer function. Lastly an equivalent system match was determined as a two part combination of α/F_s and q/F_s equivalent system matches. The first part would determine the equivalent short period frequency and damping from the α/F_s equivalent system match. The second part would hold the equivalent short period frequency and damping values fixed while determining an equivalent q/F_s transfer function.

The low order equivalent system transfer functions were generated using LONGFIT and NAVFIT (references f and g). LONGFIT was used to determine the equivalent transfer functions for the simultaneous q/F_s and $n_{z_{cg}}/F_s$ or n_{z_p}/F_s matches as well as the matches using only the q/F_s transfer function. NAVFIT was used to determine the equivalent α/F_s transfer functions. The equivalent system programs provided an option to let the $1/T_{\theta_2}$ value to be fixed or free. For all applicable cases $1/T_{\theta_2}$ was fixed at the airframe value for the initial match. The $1/T_{\theta_2}$ value was then freed to determine if a better and more reasonable match could be attained. The resulting equivalent system match results were plotted against the criteria boundaries. There has been some question as to whether the more stringent Category A requirements are more applicable for the flared landing task as compared to Category C requirements. When possible both Category A and C boundaries were considered in this study.

The transient peak ratio, rise time, effective delay criteria called for the pitch rate response to a step pitch controller input calculated for the two-degree-of-freedom equations of motion. The discussion in the background portion of the Handbook for this requirement implied that if phugoid residues did not prohibit defining a short period steady state pitch rate then a short period approximation was not necessary, while if large phugoid effects were present then the short period approximation should be applied. For this study, the transfer functions were relatively simple and in many cases the phugoid residues were small. Four configurations, 1, 4, 8 and 13, did display phugoid effects and the short period approximation was applied to these configurations.

The Handbook gives maximum and minimum Δt values for the terminal and nonterminal flight phases corresponding to Category C and B requirements. In addition Δt limits were derived using Category A CAP boundaries. Also several of the configurations were overdamped and the ratio, $\Delta q_2/\Delta q_1$, was essentially undefined ($\Delta q_2/\Delta q_1 = 0/0$). For those cases the maximum MIL-F-8785C damping requirements were applied to the short period transfer function values.

The original transfer functions were used to evaluate the remaining criteria. In cases where the piloted input could be either stick force or deflection, the piloted stick force input was used.

As was mentioned in the beginning of this section, flying qualities criteria other than those listed in the Handbook were also considered. The angle of attack time history envelope was developed in a previous Calspan study (reference h). It is shown in Figure 11 and is based on data used to develop MIL-F-8785B (reference i).

The time domain predictive handling qualities criterion was developed based on the slopes of the angle of attack and n_{z_c} responses as shown in Figure 12. Also considered were time delay and pitch sensitivity metrics. Reference b gives the development of this criterion. The resulting predictive equation is

$$PHQR' = 1.7\dot{\alpha}' - 1.44\, N_{zp} + 0.55\, T_\alpha' + TD' + \dot{q}' + 2.0$$

where

$PHQR'$	=	Predicted Handling Qualities Rating
$\dot{\alpha}'$	=	as defined in Figure 12 (ΔHQR)
N_{zp}	=	as defined in Figure 12 (ΔHQR)
T_α'	=	as defined in Figure 12 (ΔHQR)
TD'	=	time delay metric, $0.02\,(TDq - 100)\,(\dot{q}/lb)/0.45$, ($\Delta$HQR)
TDq	=	time from wheel controller pitch force step input to maximum slope intercept of the resultant pitch rate response (ms). See Figure 13. When TD is less than 100 ms, let $TD' = 0$.
$\dot{q}/lb$	=	pitch sensitivity measured by the maximum slope pitch rate responses to a step input divided by the pitch force (deg/sec^2/lb)
0.45	=	nominal optimal sensitivity for wheel controllers (deg/sec^2/lb)
0.02	=	nominal slope for sensitivity lines (HQR/ms)
100	=	time delay threshold for the flared landing task (ms)
$\dot{q}'$	=	sensitivity metric, $\left\lvert \dfrac{\dot{q}/lb - 0.45}{0.2} \right\rvert$, ($\Delta$HQR)
0.2	=	allowable sensitivity range for wheel controllers (deg/sec^2/lb)
2.0	=	bias term where a "criteria perfect" ($\dot{\alpha}' = N_{zp} = T_\alpha' = TD' = \dot{q}' = 0$) configuration would yield a HQR of 2.

These values are based on wheel controllers.

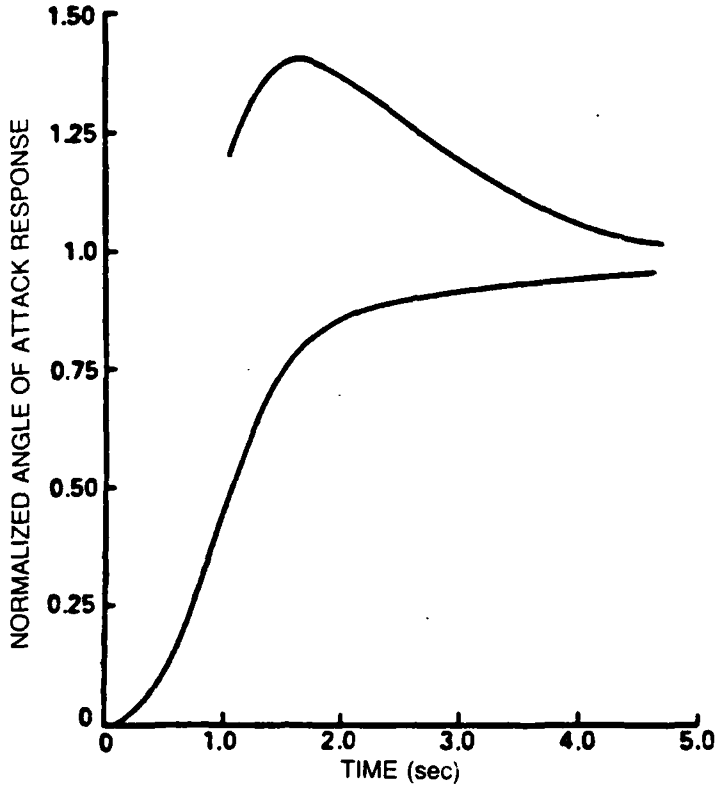
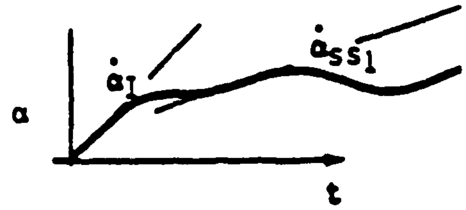
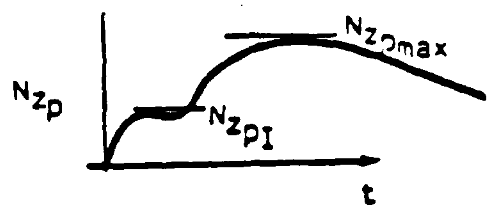


FIGURE 11 NORMALIZED ANGLE OF ATTACK RESPONSE TIME HISTORY RESPONSE ENVELOPE

$\dot{\alpha}' = \dot{\alpha}_{ss} / \dot{\alpha}_I$ where:

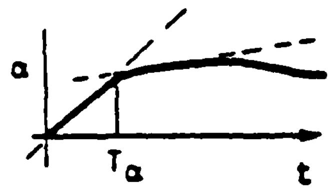


$N_{z_p} = N_{z_{pI}} / N_{z_{p\,max}}$ where:



$$T'_\alpha = |T_\alpha - 1| \begin{bmatrix} |\dot{\alpha}'| + 0.05 \\ |N'_{z_p}| + 0.05 \end{bmatrix}$$

when: $T'_\alpha > 6$ let $T'_\alpha = 6$, and T_α is defined by



and when: $T_\alpha <$ let $T'_\alpha = 0$

FIGURE 12 PREDICTIVE HANDLING QUALITIES METRICS
(Reference b)

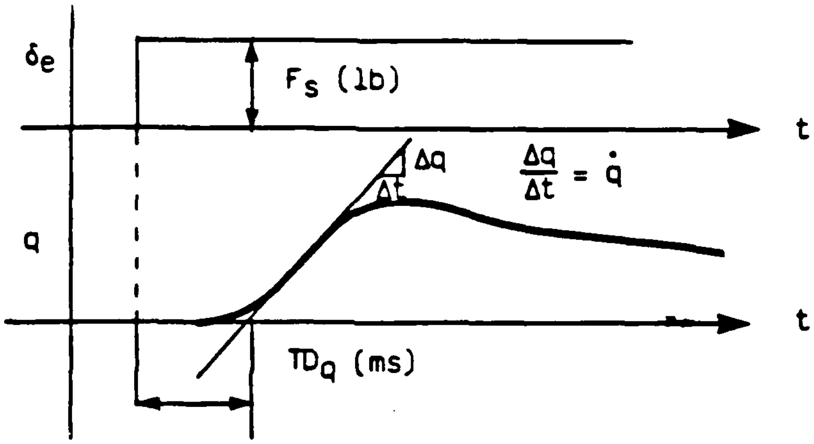


FIGURE 13 DEFINITION OF TD_q
(Reference b)

1.5 TEST CONFIGURATION DESCRIPTION

The aircraft model used in the flared landing flying qualities study was a generic medium size transport. The model characteristics were as follows:

Weight (W)	=	193,000 lbs.
Mass (m)	=	5999.4 slugs
Wing Area (S)	=	2174 ft^2
Wing Span (b)	=	157 ft
Wing Chord ($\bar{c}$)	=	15.074 ft
Ixx	=	4,003,900 slug-ft^2
Iyy	=	5,408,500 slug-ft^2
Izz	=	9,184,470 slug-ft^2
Ixy	=	223,410 slug-ft^2
V_{trim}	=	132 KIAS (223 fps)
$\bar{q}$	=	59.14 psf

Rather than defining a longitudinal aerodynamic model and corresponding control system for each configuration, the longitudinal transfer functions were defined by exact pole-zero placement that would generate a certain time history response corresponding to the short and long term command system. Figures 14 through 17 show the pole-zero patterns and corresponding angle of attack and pitch rate time histories to a step input. Figure 14 shows that for both a short and long term angle of attack command system (Configurations 1, 5, 13) the phugoid poles cancel the angle of attack zeros so that the angle of attack response is a pure second order response. In the pitch rate response there is no pole-zero cancellation resulting in the time history response displaying phugoid effects. Figure 15 corresponds to configurations 2, 6, and 14 which are pitch rate command systems in both the long and short term. Poles and zeros of the pitch rate transfer function cancel so that the pitch rate time history displays a first order response. The angle of attack response is ramplike since there is no pole-zero cancellation. The hybrid systems were combinations of the angle of attack and pitch rate command systems, i.e. a short term angle of attack command system would have a long term pitch rate command system (Configurations 3 and 7) and vice-versa (Configurations 4 and 8).

Figure 16 corresponds to the short term angle of attack and long term pitch rate command system. In the pitch rate transfer function, the phugoid poles cancel the pitch rate zero and $1/T_{\theta_1}$, eliminating any phugoid effects. The oscillatory short period roots and the $1/T_{\theta_2}$ zero produce an initial overshoot in the pitch rate response before the response reaches a steady state pitch rate value. There is no pole-zero cancellation in the angle of attack transfer function so both the short period and phugoid effects are evident in the time history response. The short term pitch rate, long term angle of attack representation is shown in Figure 17. The angle of attack transfer function shows pole-zero cancellation for the phugoid, but due to the two real short period roots the response is first order in nature. The pitch rate transfer function shows a pole-zero cancellation at $1/T_{\theta_2}$. The remaining short period pole provides an initial first order response, but phugoid effects cause the pitch rate response to return to zero.

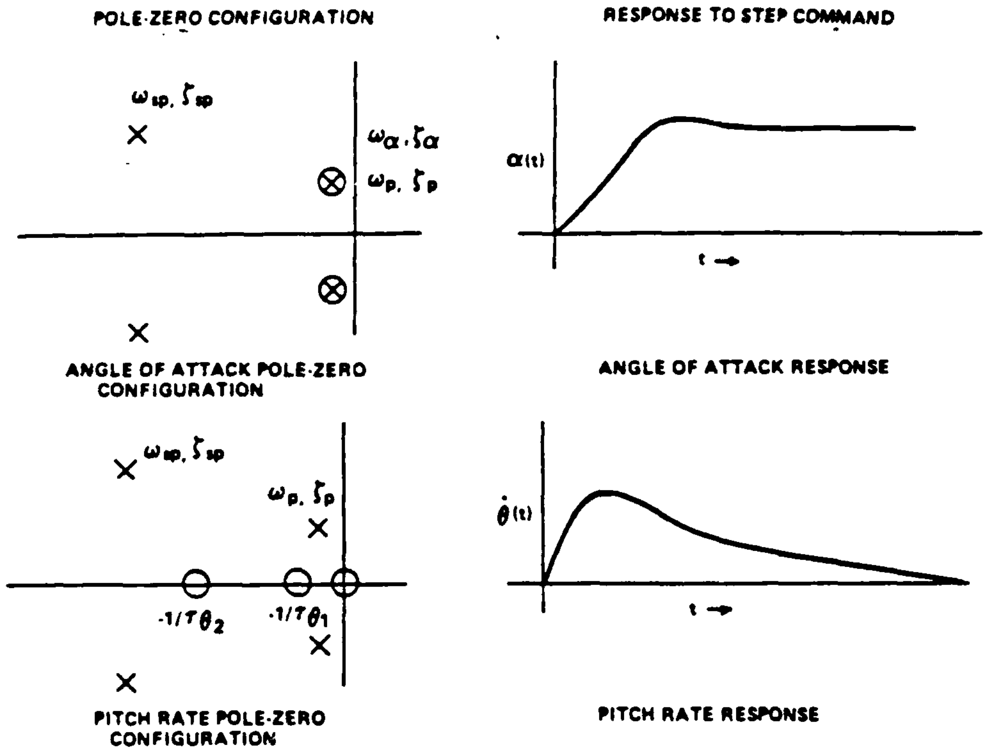


FIGURE 14 ANGLE OF ATTACK COMMAND SYSTEM
(Reference b)

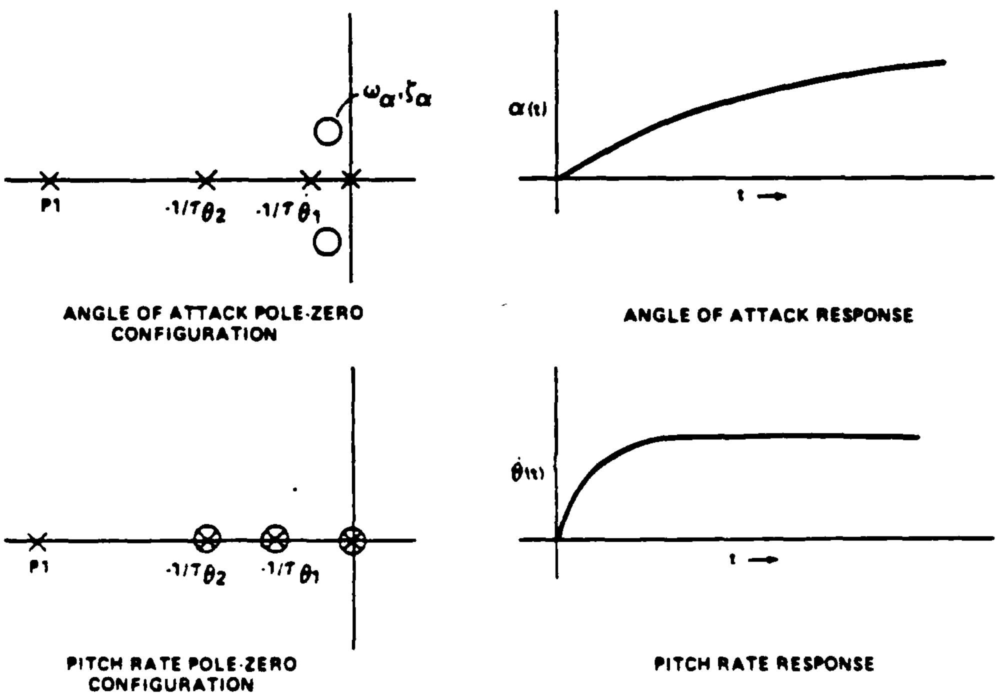


FIGURE 15 PITCH RATE COMMAND SYSTEM
(Reference b)

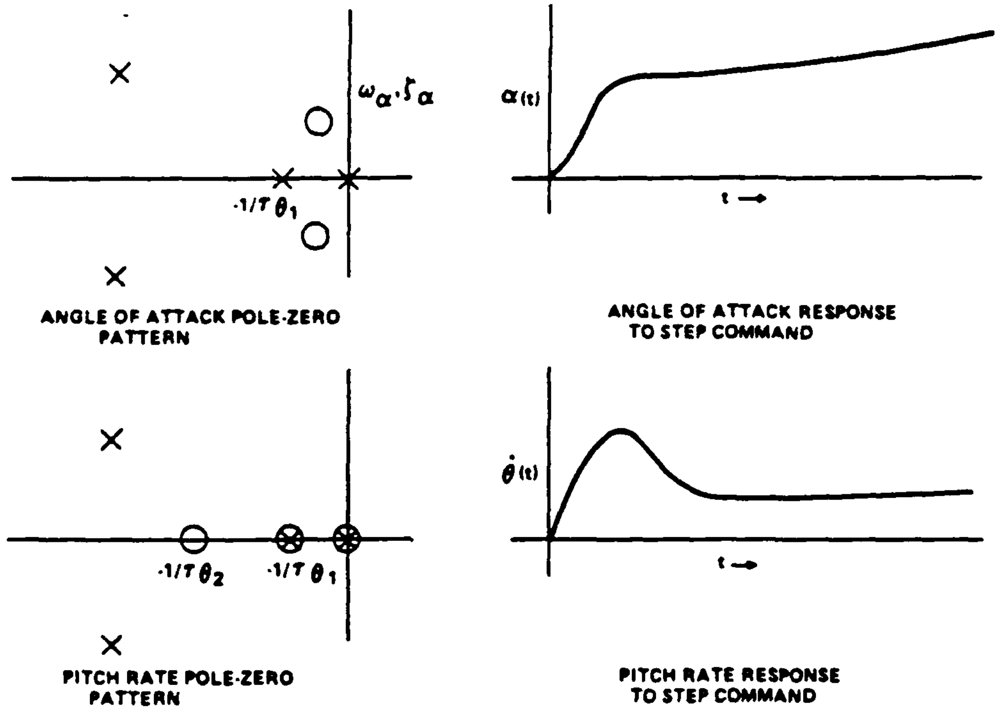


FIGURE 16 SHORT TERM ANGLE OF ATTACK, LONG TERM PITCH RATE COMMAND SYSTEM
(Reference b)

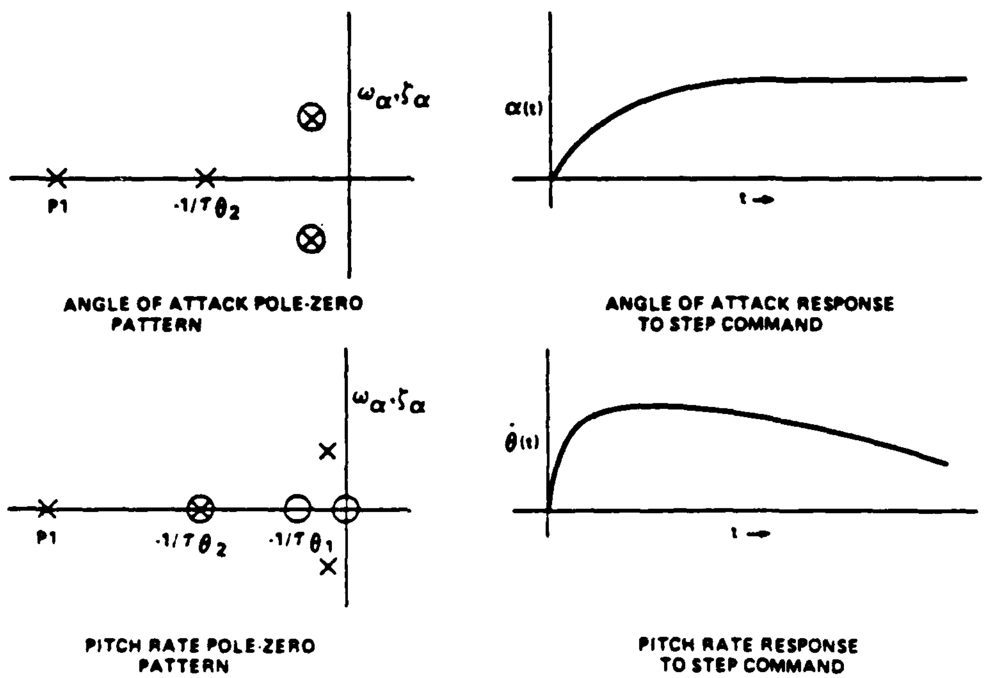


FIGURE 17 SHORT TERM PITCH RATE, LONG TERM ANGLE OF ATTACK COMMAND SYSTEM
(Reference b)

The flight path rate ($\dot{\gamma}$) command systems (Configurations 11 and 12) provided a well damped second order $n_{z_{cg}}$ response (Figure 18). The resulting pitch rate response may be either first or second order in nature depending on the pole locations of the denominator. The angle of attack response was ramplike for both configurations.

The associated time and frequency responses for each configuration are presented in Appendix A. Appendix B contains the state space representation and associated transfer functions for each configuration.

2.0 RESULTS AND DISCUSSION

The results of this study were based on the average Cooper-Harper handling qualities rating (HQR) of each configuration for both the approach and flared landing task. Figures 19 and 20 show the resulting average pilot ratings and standard deviations for the two flight tasks. In only one case was a pilot rating thrown out. Pilots A and F gave configuration 11 ($\dot{\gamma}$ command) pilot ratings of 7 and 8 respectively. They complained of entering into a PIO (Pilot Induced Oscillation). Pilot G did mention the presence of a slight PIO tendency, but it did not affect his rating of HQR = 2. Such a large span between ratings with the three pilots mentioning the presence of PIOs gave reason to suspect the 2 and therefore it was not considered in the total average rating.

The average approach ratings (Figure 19) tended to be between 2 and 4 with configuration 12 having an HQR = 5. This indicated that the pilots did not see a large difference between the configurations. The flared landing ratings (Figure 20) showed a greater distribution in pilot ratings, and therefore more sensitivity to the different configurations. The difference in the average pilot ratings between the two flight phases indicates that the flared landing requirements and approach requirements may not necessarily be the same. That is, Category C requirements may not apply to both flight tasks. Therefore the stricter requirements of Category A were also considered in this study for their applicability to the short period requirements for the flared landing task.

Each of the following sections individually discusses the results from applying the short period requirements recommended in the Handbook as well as the alternate time domain criteria to the configurations from reference b. When applicable, modifications to the requirements are presented to provide a better correlation to the predicted handling qualities levels and the actual pilot ratings. Since this study considered the effects of applying various equivalent system techniques, the CAP and $\omega_{sp}T_{\theta_2}$ criteria are both discussed in Section 2.1. Section 2.8 presents a summary of the results.

2.1 EQUIVALENT SYSTEMS

Five equivalent system matching techniques were applied to the transfer functions from each configuration. The methods used were as follows:

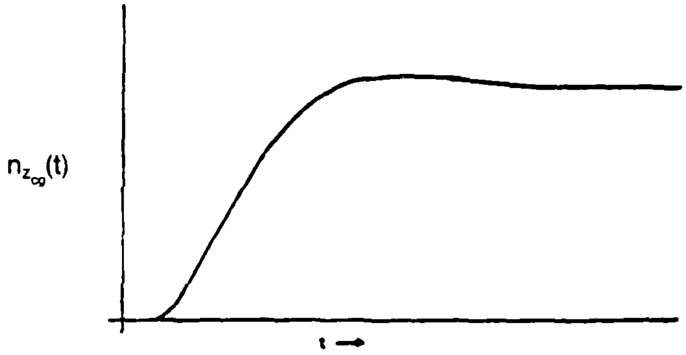
simultaneous q/F_s and n_{z_p}/F_s match

simultaneous q/F_s and $n_{z_{cg}}/F_s$ match

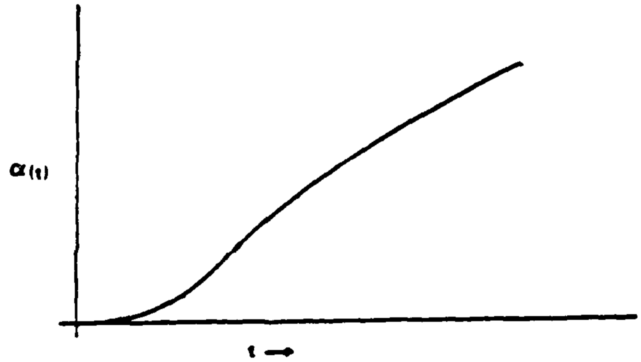
q/F_s match only

α/F_s match only

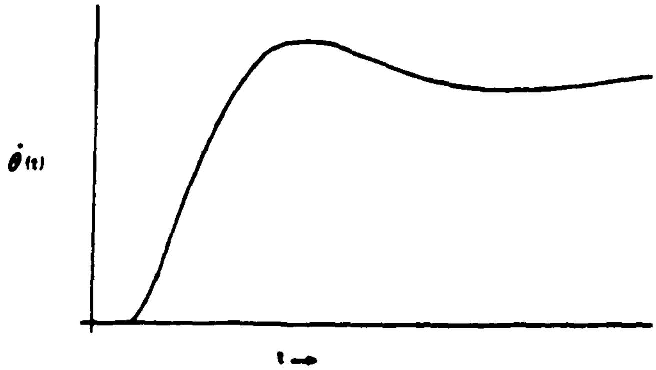
two part α/F_s match for ω_{sp} and ζ_{sp}, then q/F_s match for $1/T_{\theta_2}$.



NORMAL ACCELERATION RESPONSE
TO STEP COMMAND



ANGLE OF ATTACK RESPONSE
TO STEP COMMAND



PITCH RATE RESPONSE
TO STEP COMMAND

FIGURE 18 $\dot{\gamma}$ COMMAND SYSTEM
TIME HISTORY RESPONSES

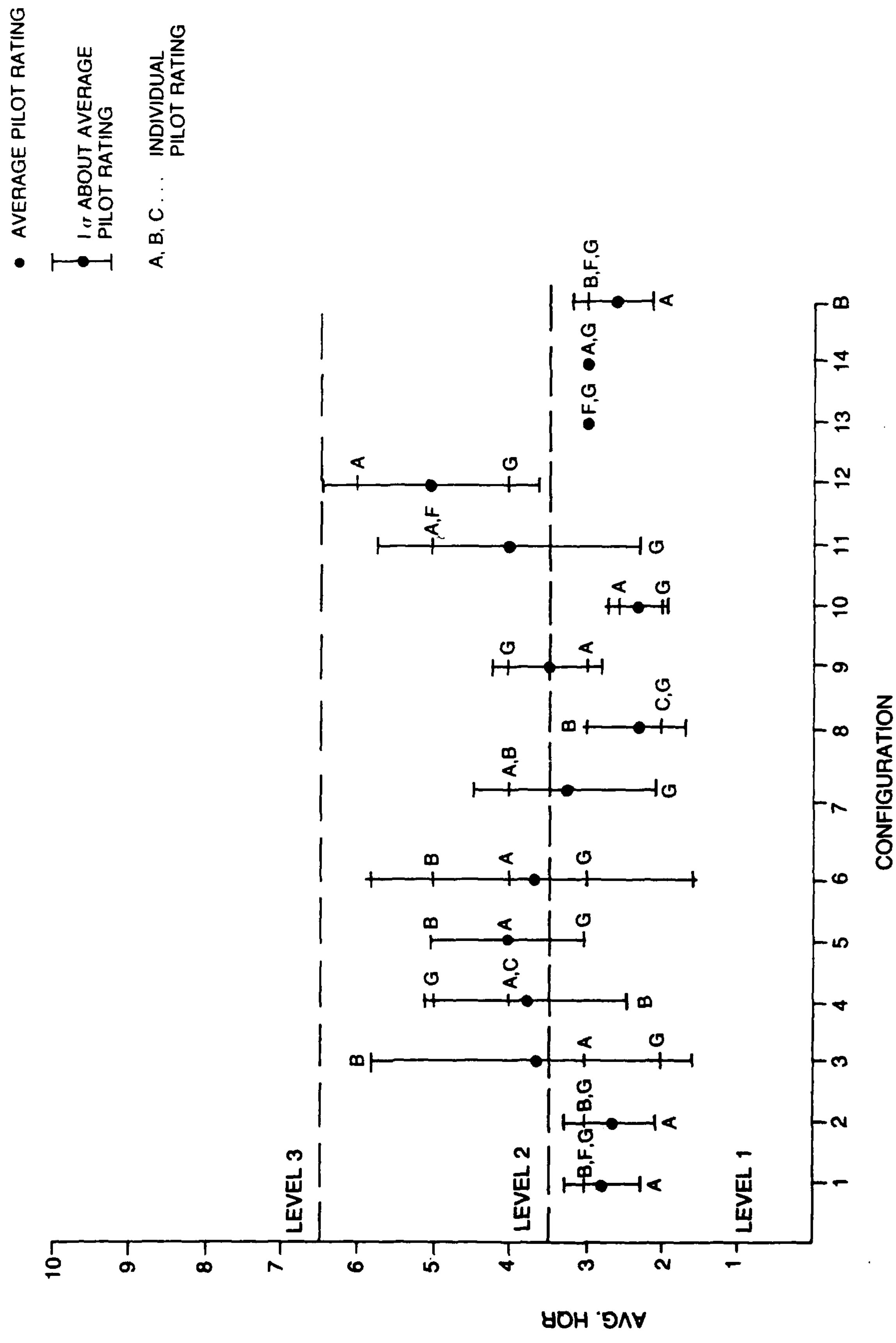


FIGURE 19 AVERAGE APPROACH PILOT RATINGS

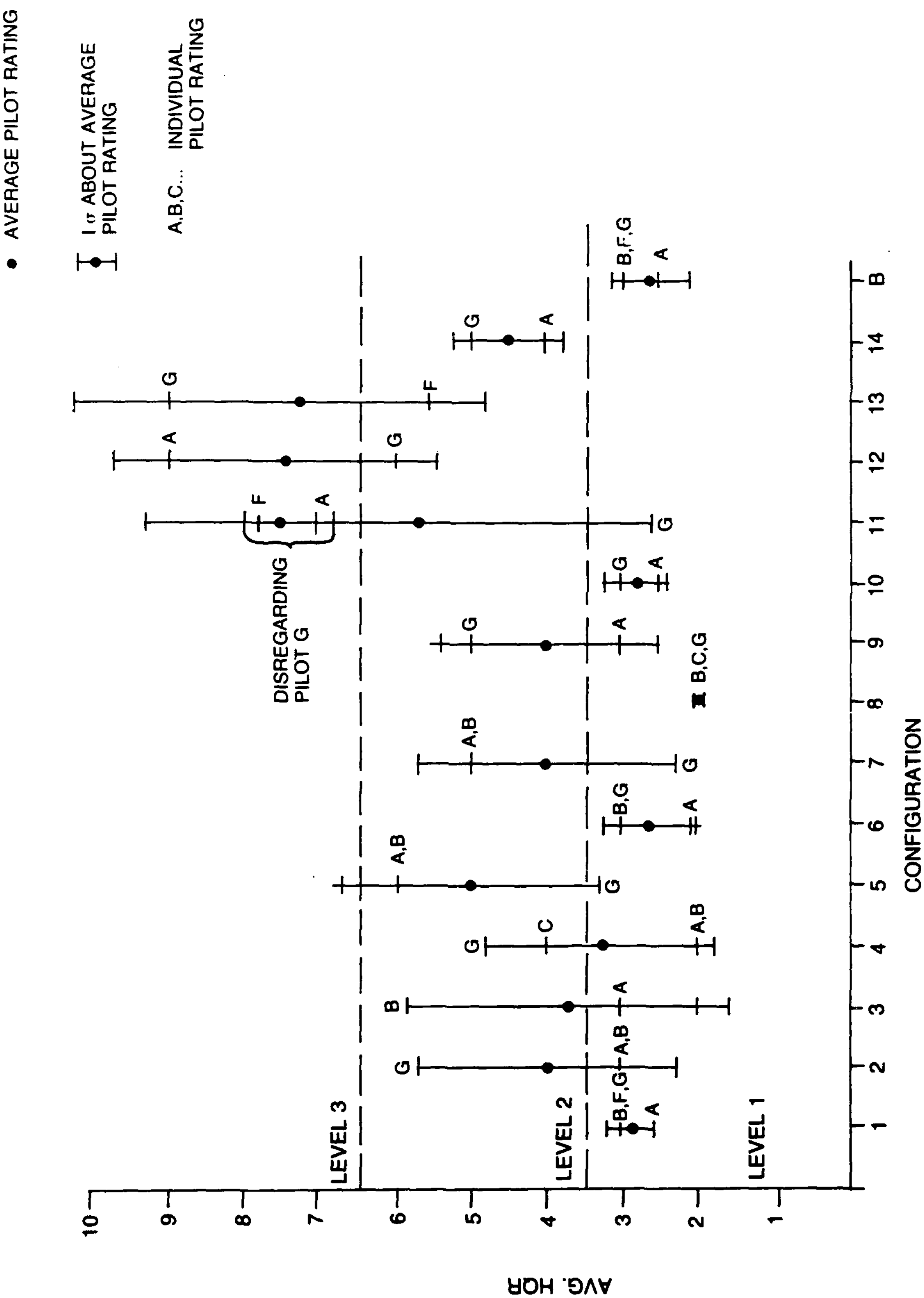


FIGURE 20 AVERAGE FLARED LANDING PILOT RATINGS

The equivalent system programs provided an option to let the $1/T_{\theta_2}$ value be fixed or free. For all applicable cases $1/T_{\theta_2}$ was fixed at the airframe value for the initial match. The $1/T_{\theta_2}$ value was then freed to determine if a better and more reasonable match could be attained. The resulting values are listed in Appendix C.

The equivalent system values were then plotted against the CAP vs ζ_{sp} and $\omega_{sp}T_{\theta_2}$ vs ζ_{sp} for both Category A and C requirements. In addition the ω_{sp} vs n/α requirements from MIL-F-8785C were also considered. Figures 21 through 23 are the results from the simultaneous q/F_s and n_{z_p}/F_s match for the three criteria listed. Appendix D.1 contains the remaining plots for each equivalent system match. Presented in Table 2 is a summary of the overall results for both the approach and flared landing tasks using each equivalent system matching technique. The numbers listed in the Table are the percentage of cases in which the average pilot ratings corresponded with the predicted handling qualities levels.

These results shed little light on whether $1/T_{\theta_2}$ should be fixed or free. Inherent in the nature of the "two part α/F_s then q/F_s match" 1/T02 is free. The resulting $1/T_{\theta_2}$ values from the two part match on the whole were reasonable and in the general area of the original $1/T_{\theta_2}$ values. In other cases, the equivalent $1/T_{\theta_2}$ values were not as consistent and were either rather large or small. Such was the case for the simultaneous q/F_s and $n_{z_{cg}}/F_s$ match where in a majority of the cases values for $1/T_{\theta_2}$ were greater than 4 and in one case (Configuration 4) $1/T_{\theta_2}$ was as high as 22.8. Such a dilemma may be avoided in the case where the simultaneous q/F_s and n_{z_p}/F_s match was used. (Note: this corresponds to method recommended in the Handbook.) In this case the same results were reached either with or wihtout $1/T_{\theta_2}$ free. Using this method and keeping $1/T_{\theta_2}$ fixed allows the same correlation with pilot ratings while still maintaining the significance of $1/T_{\theta_2}$.

From the results listed in Table 2, it can be seen that for the approach task the simultaneous q/F_s and n_{z_p}/F_s match provides the best overall correlation with pilot ratings for the three criteria used. There are other cases which similar results occur, e.g. q/F_s match using ω_{sp} vs n/α criteria. Both the two part α/F_s then q/F_s match with $1/T_{\theta_2}$ free generated the same flared landing results for Cateogry A ω_{sp} vs n/α. The two part match provided the best correlation for the CAP vs ζ_{sp} criteria while the q/F_s match with $1/T_\theta$ free provided the best correlation for $\omega_{sp}T_\theta$ vs ζ_{sp} criteria. None of the results showed very good correlation with the average pilot ratings.

2.2 TRANSIENT PEAK RATIO, RISE TIME, EFFECTIVE DELAY

Presented in Table 3 are the limits for the effective time delays, rise time and transient peak ratios as defined by the Handbook for the terminal flight phase. In addition, alternate rise time limits were defined from Category A CAP requirements and are also presented in Table 3. This was done because the Handbook presents the rise time limits in terms of terminal and nonterminal flight phases derived from relaxed Category C requirements. Based on the results from the 15 configurations used in this study, the pilots were more critical of the flared landing than the approach task. It would appear then, that instead of relaxing the maximum effective rise times, they should be constricted toward Category A requirements. Both the recommended Handbook and the equivalent Category A Δt values were considered in this study.

TABLE 2 EQUIVALENT SYSTEM RESULTS

EQUIVALENT SYSTEM MATCH	HANDLING QUALITIES CRITERIA	APPROACH $1/T_{\theta_2}$ FIXED	APPROACH $1/T_{\theta_2}$ FIXED OR FREED	FLARED LANDING $1/T_{\theta_2}$ FIXED	FLARED LANDING $1/T_{\theta_2}$ FIXED OR FREE
q/F_s ONLY	ω_{sp} VS. n/α, ζ_{sp}, CAT A	47	40	40	47
	ω_{sp} VS. n/α, ζ_{sp}, CAT C	53	41	33	40
	CAP vs ζ_{sp}, CAT A	40	33	20	27
	CAP vs ζ_{sp}, CAT C	40	47	13	13
	$\omega_{sp}T_{\theta_2}$ vs ζ_{sp} CAT A	27	27	27	40
	$\omega_{sp}T_{\theta_2}$ vs ζ_{sp}, CAT C	33	27	20	33
α/F_s ONLY	ω_{sp} vs n/α, ζ_{sp}, CAT A	33	N/A	33	N/A
	ω_{sp} vs n/α, ζ_{sp}, CAT C	40		20	
	CAP vs ζ_{sp}, CAT A	27		13	
	CAP vs ζ_{sp}, CAT C	33		13	
	$\omega_{sp}T_{\theta_2}$ vs ζ_{sp}, CAT A	20		27	
	$\omega_{sp}T_{\theta_2}$ vs ζ_{sp}, CAT C	20		20	
2 PART α/F_s THEN q/F_s	ω_{sp} vs n/α, ζ_{sp}, CAT A	N/A	33	N/A	47
	ω_{sp} vs n/α, ζ_{sp}, CAT C		47		27
	CAP vs ζ_{sp}, CAT A		40		47
	CAP vs ζ_{sp}, CAT C		47		47
	$\omega_{sp}T_{\theta_2}$ vs ζ_{sp}, CAT A		27		33
	$\omega_{sp}T_{\theta_2}$ vs ζ_{sp}, CAT C		33		27
SIMULTANEOUS q/F_s AND $n_{z_{cg}}/F_s$	ω_{sp} vs n/α, ζ_{sp}, CAT A	40	40	33	33
	ω_{sp} vs n/α, ζ_{sp}, CAT C	47	47	13	20
	CAP vs ζ_{sp}, CAT A	33	20	13	27
	CAP vs ζ_{sp}, CAT C	33	53	13	6.7
	$\omega_{sp}T_{\theta_2}$ vs ζ_{sp}, CAT A	47	27	27	27
	$\omega_{sp}T_{\theta_2}$ vs ζ_{sp}, CAT C	20	27	27	27
SIMULTANEOUS q/F_s AND n_{z_p}/F_s	ω_{sp} vs n/α, ζ_{sp}, CAT A	53	40	40	13
	ω_{sp} vs n/α, ζ_{sp}, CAT C	47	47	6.7	13
	CAP vs ζ_{sp}, CAT A	47	47	20	27
	CAP vs ζ_{sp}, CAT C	47	53	6.7	6.7
	$\omega_{sp}T_{\theta_2}$ vs ζ_{sp}, CAT A	47	47	27	27
	$\omega_{sp}T_{\theta_2}$ vs ζ_{sp}, CAT C	53	53	20	20

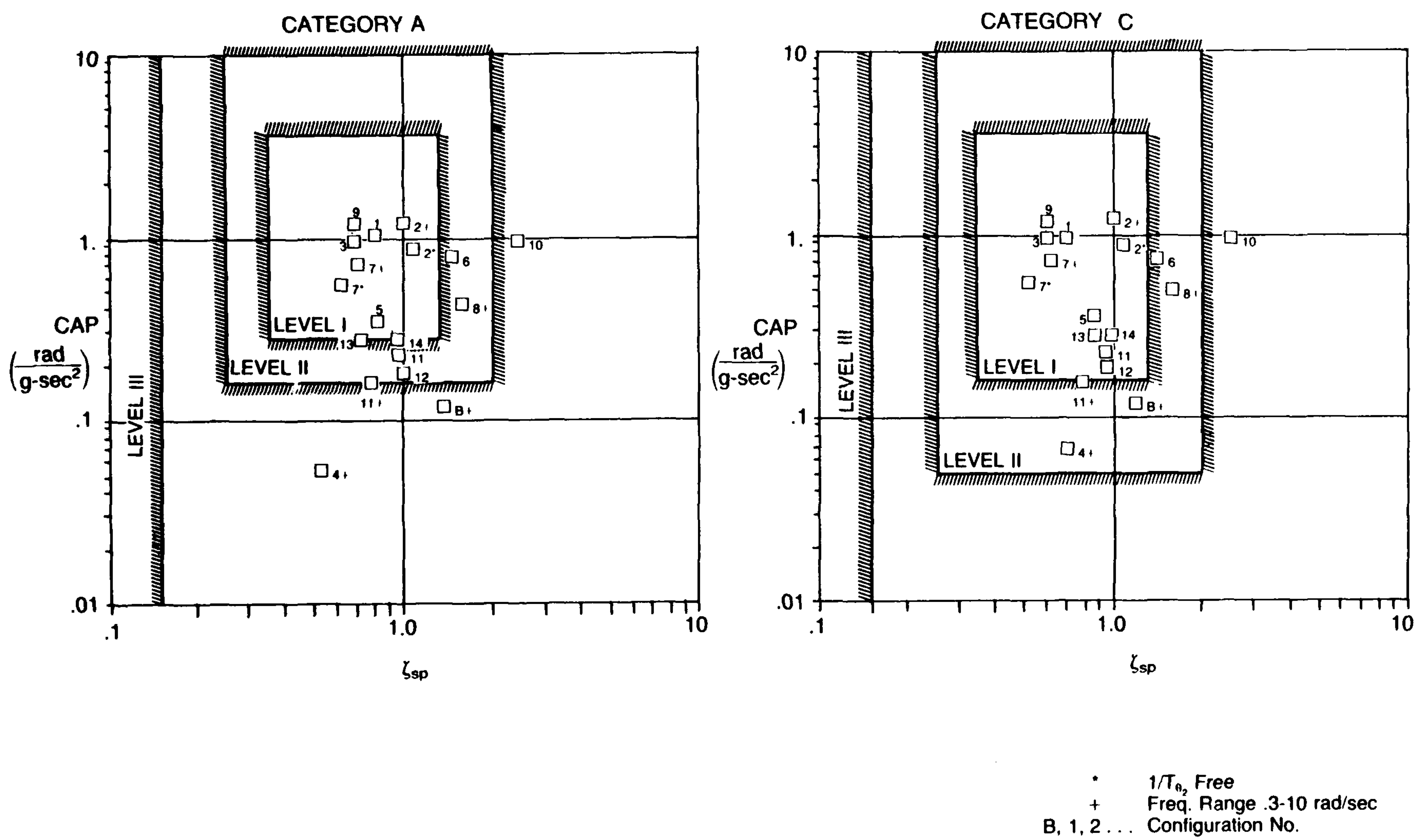
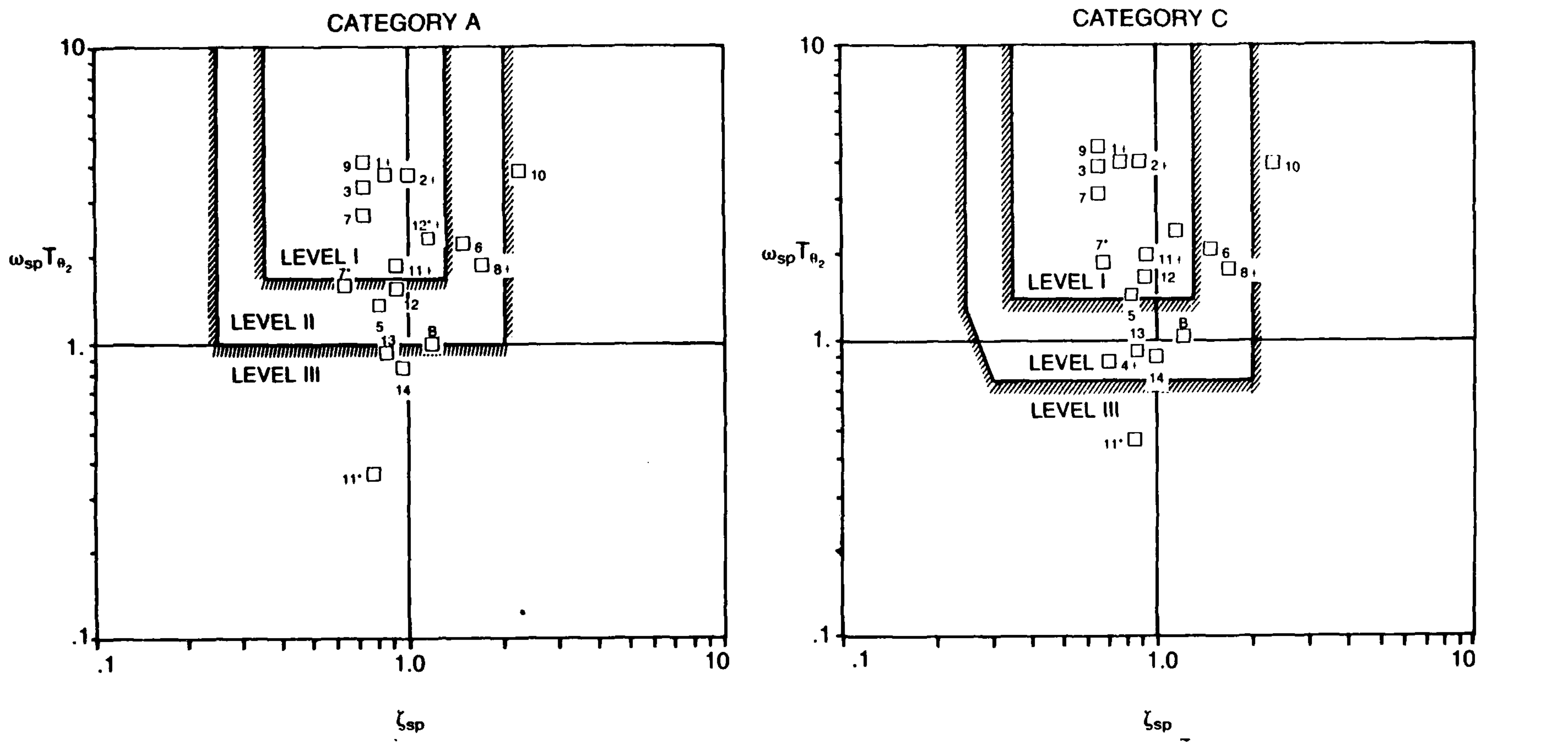
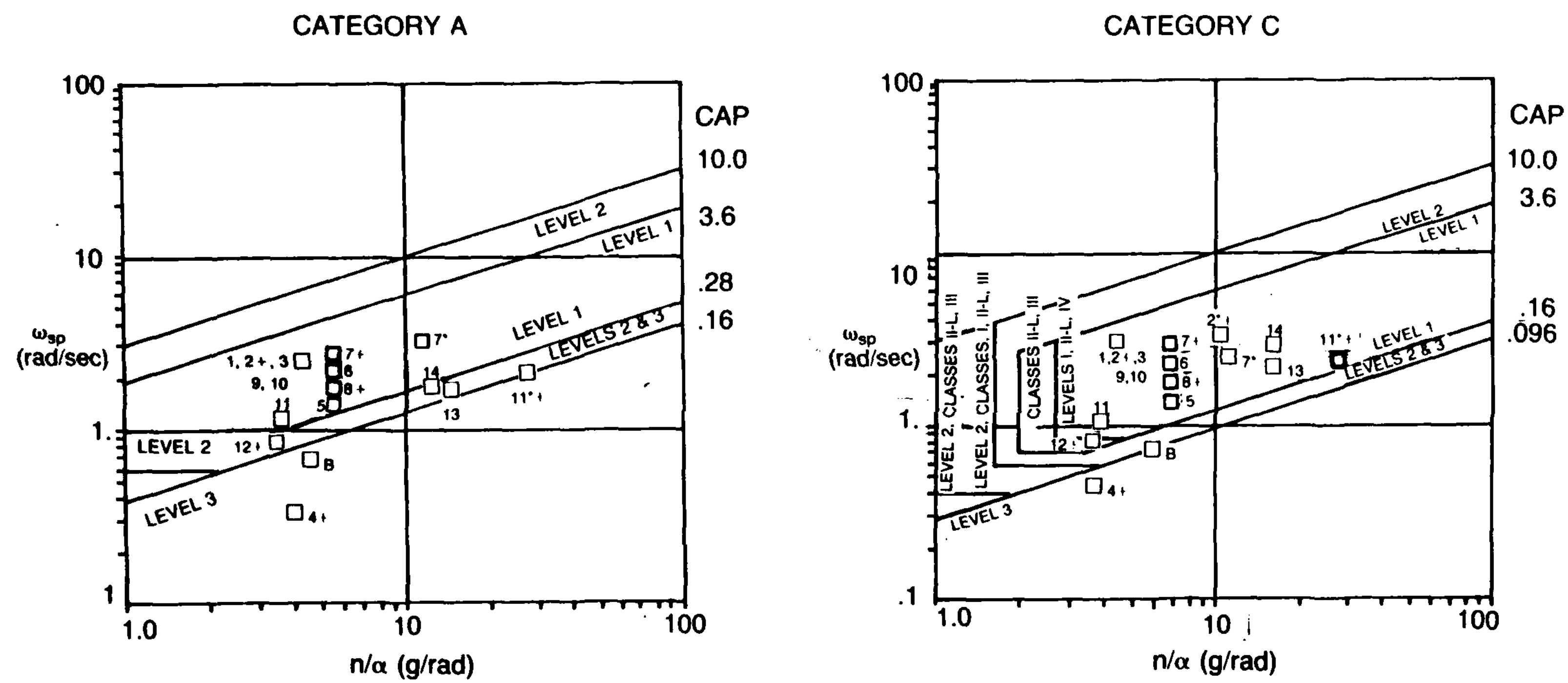


FIGURE 21 CAP VS. ζ_{sp}
SIMULTANEOUS q/F_s AND n_{z_p}/F_s
EQUIVALENT SYSTEM MATCH



* $1/T_{\theta_2}$ Free
\+ Freq. Range .3-10 rad/sec
B, 1, 2 . . . . Configuration No.

FIGURE 22 $\omega_{sp}T_{\theta_2}$ VS. ζ_{sp}
SIMULTANEOUS q/F_s AND n_{z_p}/F_s
EQUIVALENT SYSTEM MATCH



* 1/T_{θ_2} Free
\+ Freq. Range .3-10 rad/sec
B, 1, 2 . . . Configuration No.

FIGURE 23 $\omega_{sp}T_{\theta_2}$ vs n/α

SIMULTANEOUS q/F_s AND n_{z_p}/F_s
EQUIVALENT SYSTEM MATCH

TABLE 3 TRANSIENT PEAK RATIO, RISE TIME, EFFECTIVE DELAY REQUIREMENTS

	TRANSIENT PEAK RATIO MAX $\Delta q_2/\Delta q_1$	EFFECTIVE DELAY t_1	EFFECTIVE RISE TIME MIN Δt	EFFECTIVE RISE TIME MAX Δt	ALTERNATE CAT. A MAX Δt
LEVEL 1	$\leq .30$	$\leq .12$	$9/V_t$	$200/V_t$	$114/V_t$
LEVEL 2	$\leq .60$	$\leq .17$	$3.2/V_t$	$645/V_t$	$200/V_t$
LEVEL 3	$\leq .85$	$\leq .21$	NOT DEFINED		NOT DEFINED

V_t = TRUE AIRSPEED (ft/sec)

The results are tabulated in Table 4. The overall predicted handling qualities level for each configuration was based on the highest level rating for each part of the criteria. From the Handbook recommended values, 53% of the predicted configurations corresponded to the approach pilot ratings while 47% of the predicted values corresponded to the flared landing pilot ratings. The maximum Δt values using Category A CAP requirements were able to improve the correlation between predicted values and pilot ratings by 1 case or up to 53% correlation for the flared landing task. In general, the transient peak ratio predicted the same level handling qualities levels as the Category A Δt requirements. The results could be improved if the maximum Level 2 damping requirements were increased from 2 to 2.1. Never did the pilots give the high damping cases a Level 3 rating as predicted in MIL-F-8785C, but rather Level 1 or 2 for both the approach and flared landing tasks. If this were the case, the correlation with pilot ratings would improve to 60% for the approach task and the flared landing task would show 53% correlation. This criterion yielded the same results as with the equivalent systems but with less effort or debate as to which equivalent system matching technique was more applicable.

2.3 BANDWIDTH, TIME DELAY

In Figures 24 and 25 the resulting bandwidth and time delays for the 15 configurations were plotted against the Category A and C boundaries for the approach and flared landing tasks. The Category C requirements corresponded with 40% of the pilot ratings for the approach task. Category A requirements corresponded with 60% of the pilot ratings for the flared landing task. These results were no better than any of the previously considered criteria (worse in fact for the approach task). The Handbook does discuss that for classical aircraft the Level 1 boundaries may be too stringent for the transport class of aircraft that was being considered in this study. (The boundaries in the Handbook were based only on highly augmented fighter aircraft.)

Reference b proposed new bandwidth boundaries for the transport class of aircraft to reflect the trend that pilots tolerate lower bandwidths and higher time delays in this class of airplane. Figure 26 shows the recommended transport boundaries and the corresponding approach and flared landing results. The flared landing correlation improved to 73% with pilot ratings, but the approach decreased to 33% correlation with pilot ratings.

TABLE 4 TRANSIENT PEAK RATIO, RISE TIME, EFFECTIVE DELAY CRITERION RESULTS

CONFIGURATION	t_1	Δt	$\Delta q_2/\Delta q_1$	PRED. LEVEL HANDBOOK	PRED. LEVEL CAT A	APPROACH RATINGS	FLARED LAND. RATINGS
1*	.06	.20	.08	1	1	1	1
2	.06	.20	(%)ζ = 2.1	3	3	1	2
3	.06	.22	.07	1	1	2	2
4*	.06	.25	(%)ζ = 2.1	3	3	2	1
5	.06	.40	.33	2	2	2	2
6	.06	.24	(%)ζ = 1.3	1	1	2	1
7	.06	.23	0	1	1	1	2
8*	.06	.38	(%)ζ = 1.3	1	1	1	1
9	.06	.22	.11	1	1	1/2	2
10	.06	.24	(%)ζ = 2.1	3	3	1	1
11	.19	.83	−3	3	3	2	3
12	.20	.86	−.29	3	3	2	3
13*	.06	.60	0	1	2	1	3
14	.06	.63	(%)ζ = 1	1	2	1	2
B	.06	.25	.15	1	1	1	1

* — Short Period Approximation

(%) — Used MIL-F-8785C Damping Requirements

NOTES:

Handbook Correlation: Approach — 53%; Flared Landing — 47%

Category A Correlation: Flared Landing — 53%

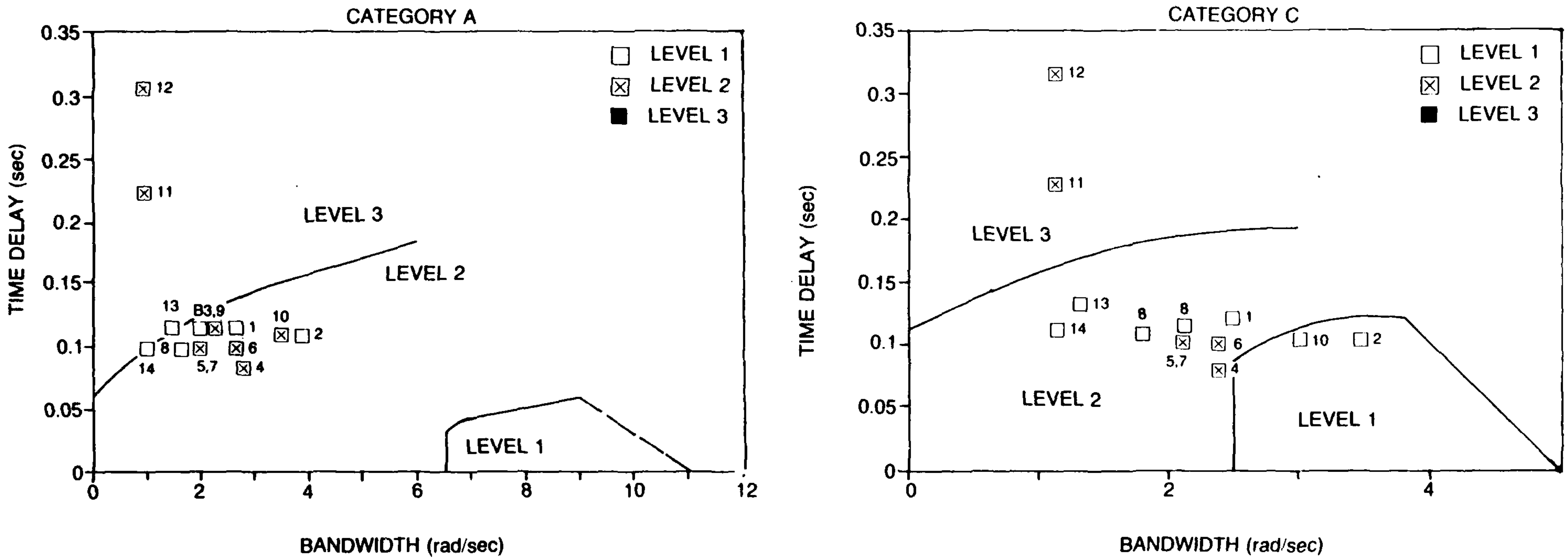


FIGURE 24 BANDWIDTH REQUIREMENT RESULTS — APPROACH

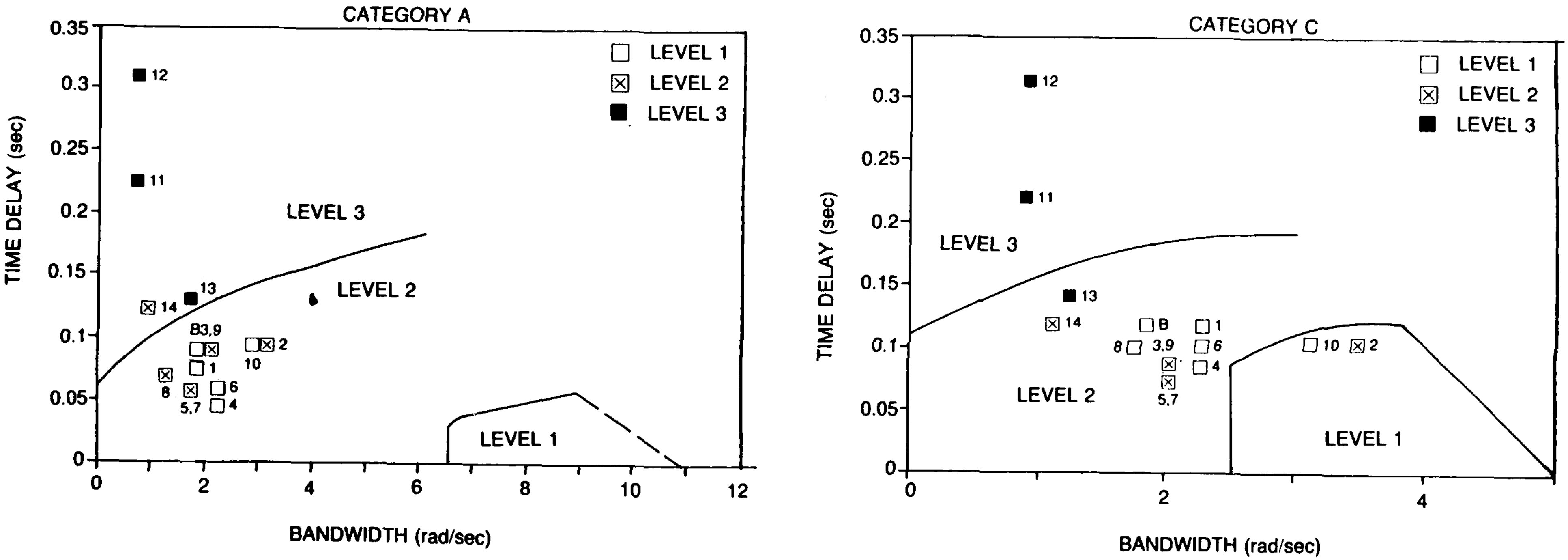
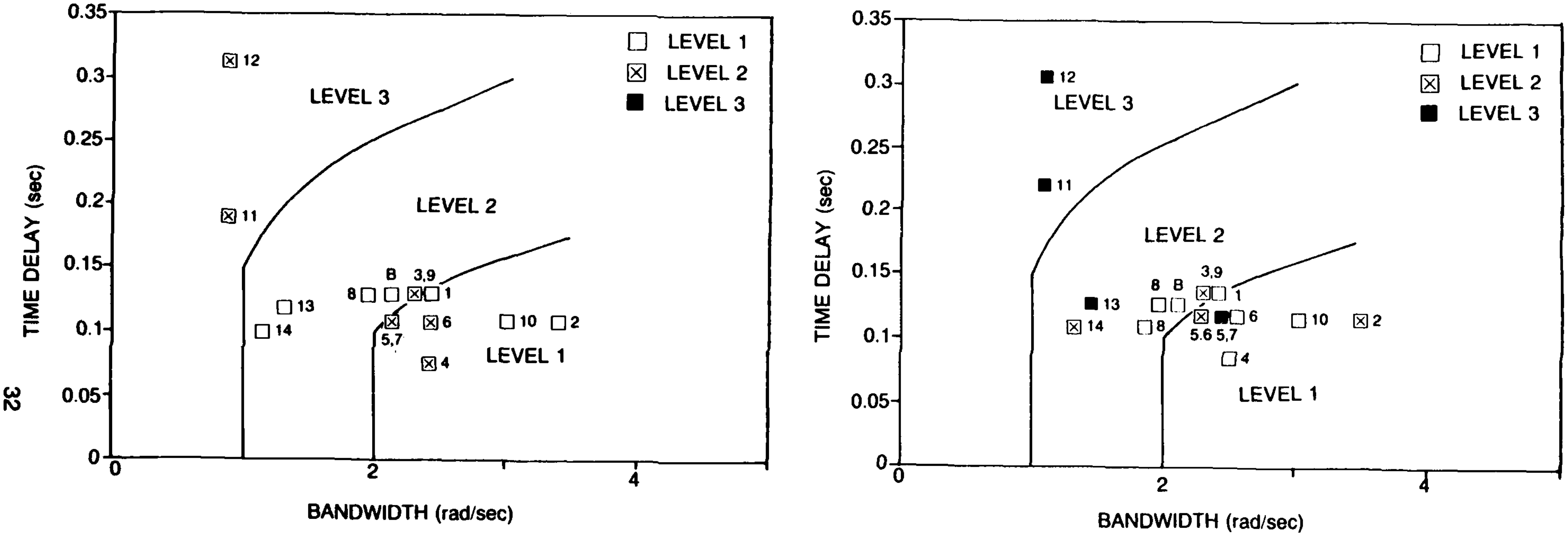


FIGURE 25 BANDWIDTH REQUIREMENT RESULTS — FLARED LANDING



a) APPROACH

b) FLARED LANDING

FIGURE 26 PROPOSED TRANSPORT BOUNDARIES

The distribution of the approach Level 1 rated configurations and the corresponding bandwidths was over the frequency range ω_{bw} = 0.9 to 3.3 rad/sec. At the same time, Level 2 rated configurations also fell within that range. This indicates that for the approach task, the bandwidth may not adequately separate Level 1 from Level 2 configurations.

In an attempt to improve the flared landing results, the Level 1 boundaries for the modified bandwidth criterion were shifted as shown in Figure 27; to both better correlate with the results from this study and those of reference b. The modified boundaries improved the correlation between the pilot ratings and predicted ratings to 80%. The correlation for the data in reference b improved slightly from 70 to 74%. These modified boundaries may better predict the landing flying qualities levels for the transport class of aircraft.

2.4 CLOSED-LOOP CRITERION

Two alternate pilot models were given as part of the closed-loop criterion. The pilot model used in this study was as follows:

$$Yp = Kp\, e^{-.25s} \frac{(\tau_{p1}s + 1)}{(\tau_{p2}s + 1)}$$

with no constraints for the Kp, τ_{p1}, and τ_{p2} values of the pilot model. To determine the pilot model values, the θ/F_s frequency response was studied to determine the additional phase and gain necessary to meet the closed-loop landing requirements. The values for τ_{p1} and τ_{p2} could be derived from the phase gain (lead compensation) necessary to produce a closed-loop phase of −90 degrees at ω = 2.5 rad/sec (*closed-loop landing requirements per reference* a). The relationships for the lead compensation are as follows:

$$G(s) = \frac{1}{\alpha}\frac{(\tau\alpha s + 1)}{(\tau s + 1)}$$

with

$$\phi \text{ required} = \sin^{-1}\left(\frac{\alpha - 1}{\alpha + 1}\right)$$

$$\omega \text{ required} = \frac{1}{\tau\sqrt{\alpha}}$$

$$\tau_{p1} = \tau\alpha$$

$$\tau_{p2} = \tau$$

(reference j). It was assumed the Kp value was a pure unitless gain term to yield 0 dB at ω = 2.5 rad/sec. The values for the pilot models to meet the landing requirements for each configuration are listed in Table 5.

Figure 28 shows the resulting closed-loop frequency response for the base case which satisfies the closed-loop requirements. Similar plots for the remaining cases are in Appendix D.2. No magnitude or phase limits were set in the Handbook for frequencies greater than ω = 2.5 rad/sec.

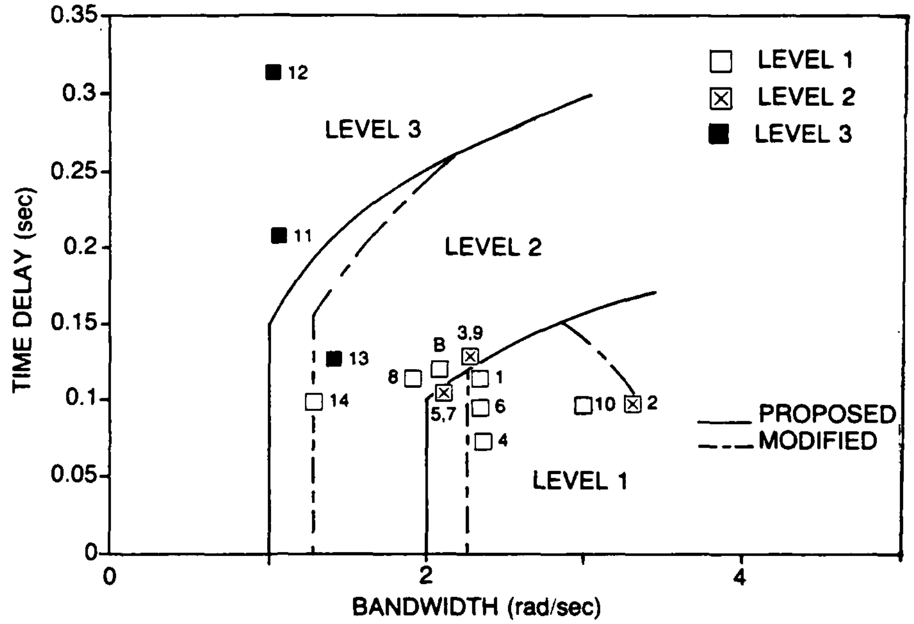


FIGURE 27 MODIFIED TRANPORT BOUNDARIES FOR THE FLARED LANDING TASK

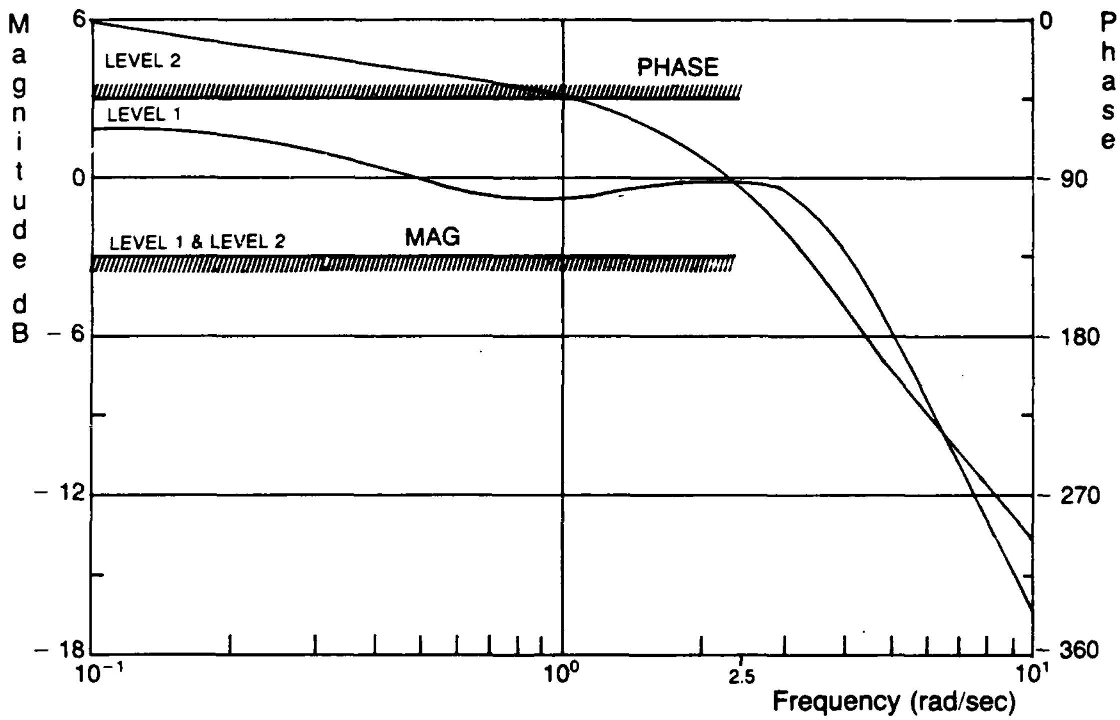


FIGURE 28 CLOSED LOOP θ/θ_c BODE PLOT — BASE CONFIGURATION

The results were that 53% of the cases corresponded with the average pilot ratings for the approach task and 33% of the cases for the flared landing task. Further analysis of the data showed a relationship between the pilot model gain and phase and pilot ratings. Figures 29 and 30 are plots of the pilot model gain vs phase for the approach and flared landing tasks. The boundaries drawn seem to separate the Level 1 gain and phase combinations from the Level 2 and 3 cases. It can be seen that the cases which required combinations of large and small gain and phase values to meet the bandwidth requirements tended to yield degraded flying qualities. The combination of both small pilot gain and phase values also yielded Level 2 or 3 pilot ratings. It is possible that a similar upper limit also exists. For the boundaries shown in Figures 29 and 30 there was 87% correlation with the average approach pilot ratings and 93% correlation with the average flared landing pilot ratings. Further studies are necessary to verify the results but the boundaries seem to define a range of acceptable pilot models. These boundaries could be used as limitations for the pilot models or as a new metric to measure the effort required to control the pitch attitude response.

TABLE 5 CLOSED-LOOP PILOT MODELS

CONFIG.	Kp GAIN	PHASE (deg)	τ_{p1} (sec)	τ_{p2} (sec)
1	4.92	35	0.77	0.21
2	7.69	40	0.86	0.19
3	4.83	10	0.48	0.34
4	3.11	10	0.48	0.34
5	1.99	25	0.63	0.25
6	3.27	25	0.63	0.25
7	2.09	25	0.63	0.25
8	2.77	30	0.69	0.25
9	1.72	15	0.52	0.31
10	3.22	10	0.48	0.34
11	2.86	50	1.01	0.15
12	9.93	65	1.80	0.09
13	2.99	50	1.01	0.15
14	4.79	55	1.27	0.13
BASE	2.65	25	0.63	0.25

2.5 DROPBACK AND NICHOLS CHART BOUNDARIES

The final recommended criterion noted in the Handbook were the guidelines developed by Gibson. Level 1, 2, or 3 boundaries were not defined since this criterion was mainly intended for fly-by-wire control law optimization. The criterion considers the step input time response of attitude, flight path and normal acceleration at the center of gravity as well as the attitude frequency response.

The criterion, as stated in the Handbook, is as follows for Category C:

a. For Category A and C flight phases, attitude dropback as defined in Figure 7 should not normally be negative, satisfactory values depend on the task and the pitch rate transients.

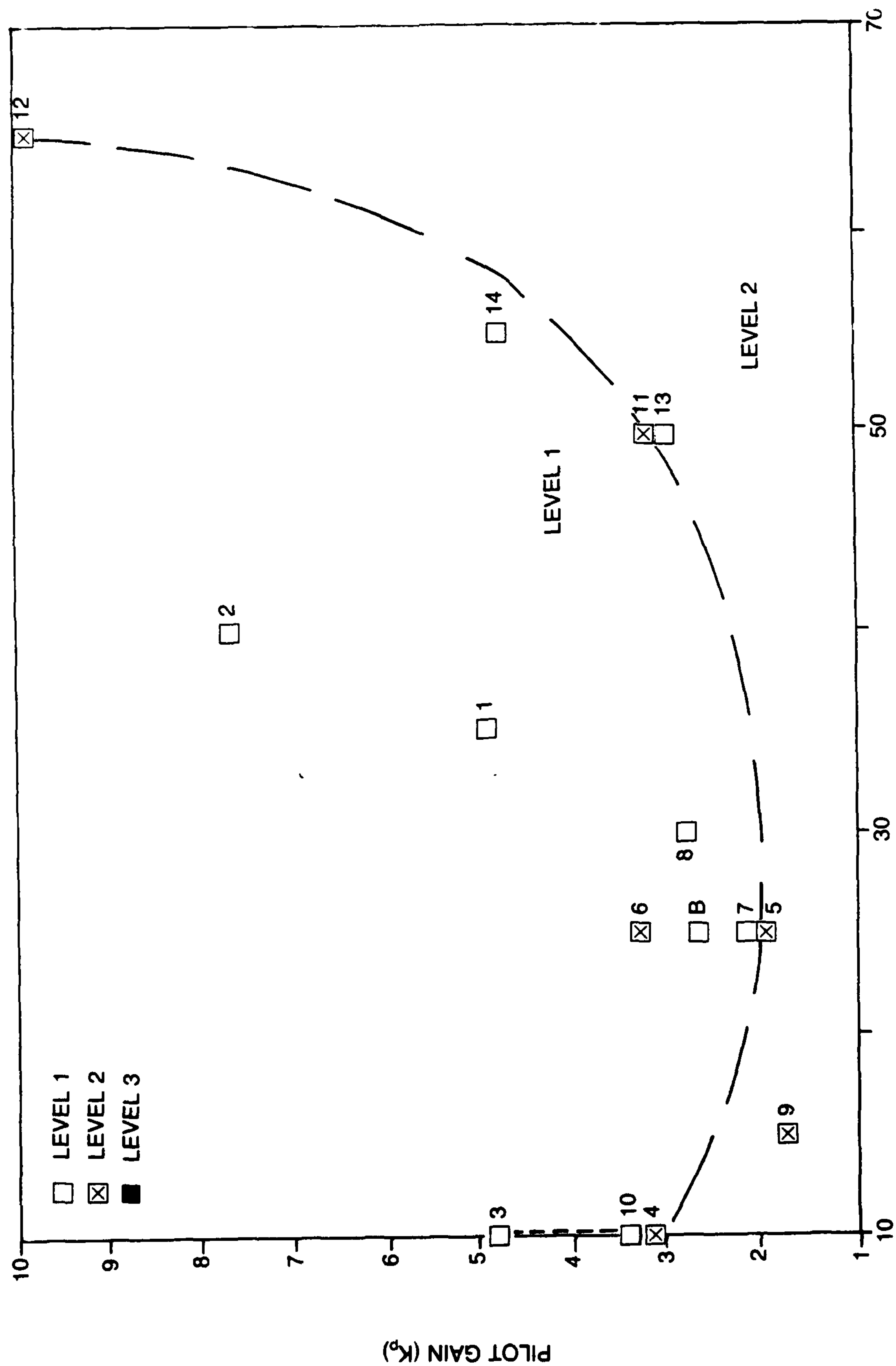


FIGURE 29 PILOT MODEL GAIN vs PHASE FOR CLOSED LOOP CRITERIA — APPROACH

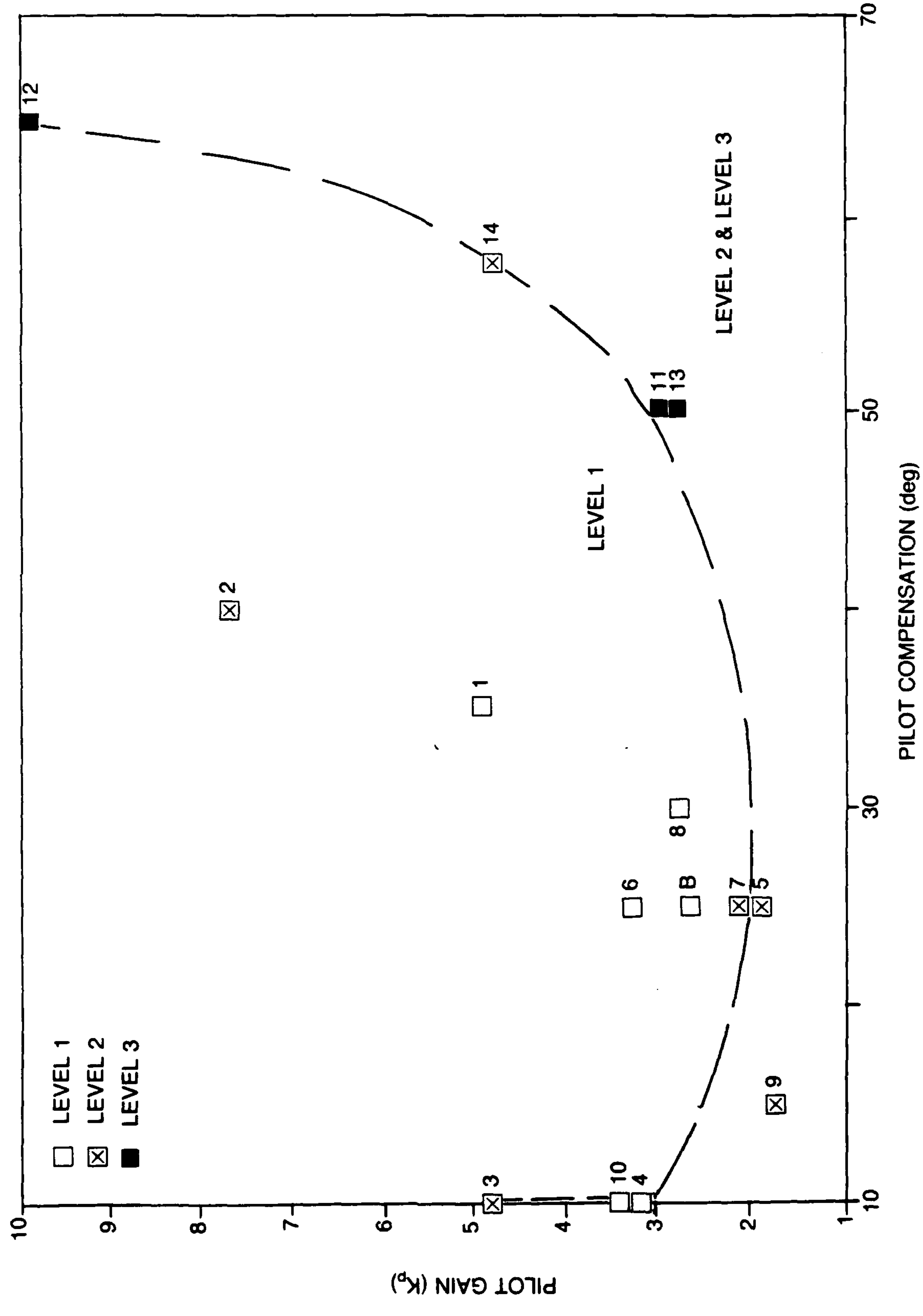


FIGURE 30 PILOT MODEL GAIN vs PHASE FOR CLOSED LOOP CRITERIA — FLARED LANDING

b. Normal acceleration responses can be related to Level 1 frequency and damping requirements by the boundaries shown on Figures 8 and 9. Any oscillation following the first peak should subside such that the ratio of successive half-cycles is less than 0.3.

c. An envelope of satisfactory Category C landing approach response for frequencies below the required bandwidth of 0.25 to .5 Hz at 120 degrees phase lag is shown in Figure 10.

d. All frequency responses must satisfy the Figure 10 requirements for response attenuation and phase lag rate of increase at the 180 degree phase lag crossover frequency.

Table 6 lists the values used in this study.

TABLE 6 DATA FOR GIBSON'S CRITERIA

CONFIG.	DROPBACK/q	τ_{n_z} (sec)	ω_{120} (Hz)	ω_{180} (Hz)	$\dot{\Phi}$ (deg/Hz)	GAIN ω_{180} (deg/lb)
1	−0.53	0.74	0.303	0.634	122.15	.0405
2	−0.4	1.00	0.303	1.004	82.73	.0152
3	−0.8	0.32	0.303	0.634	122.01	.0428
4	0.67	0.79	0.303	1.004	77.74	.0152
5	−0.13	1.32	0.252	0.578	124.49	.0489
6	−0.53	1.63	0.238	0.762	91.38	.0292
7	0.27	0.74	0.277	0.634	126.79	.0489
8	−1.33	4.58	0.199	0.762	90.10	.0314
9	1.07	0.53	0.303	0.634	122.01	.0427
10	−0.27	4.32	0.303	1.004	82.73	.0152
11	−2.67	2.26	0.110	0.303	272.90	.1362
12	−1.33	1.42	0.132	0.277	421.80	.2069
13	4	1.11	0.175	0.459	136.36	.0877
14	−1.87	1.37	0.132	0.527	105.64	.0594
B	0.8	UND	0.277	0.634	118.74	.0336

Figures 31 and 32 are plots of dropback/q values vs pilot rating for the approach and flared landing tasks. If positive values were to be considered Level 1 then there was 53% correlation with the average pilot rating for the approach task and 47% in the flared landing task. As it can be seen the results were mixed with the sign of the dropback/q value not adequately determining whether the aircraft would be rated satisfactory or not by the pilot. This poor correlation may be due to the fact that not all of the command systems used in this study had the same angle of attack or pitch rate response as recommended by Gibson (see Figure 33). Of the 15 configurations used in this study, only three (configurations 5, 7 and Baseline) had similar time histories to those shown in Figure 33. The three cases corroborated the predicted ratings for the approach task. In the flared landing task, configuration 7 was rated as Level 2 instead of the predicted Level 1.

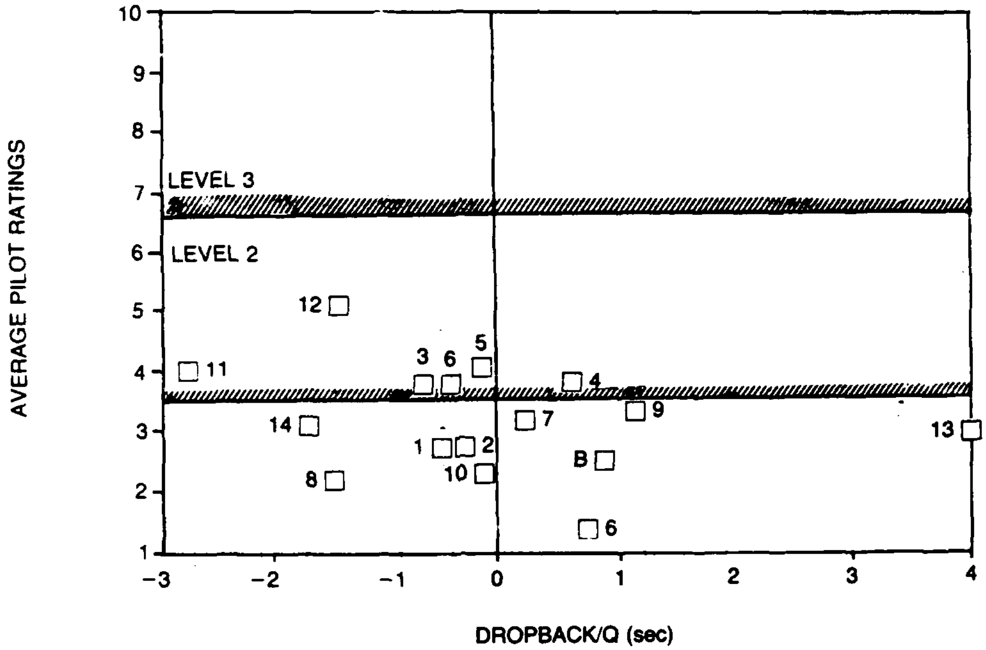


FIGURE 31 AVERAGE APPROACH PILOT RATING vs DROPBACK/q

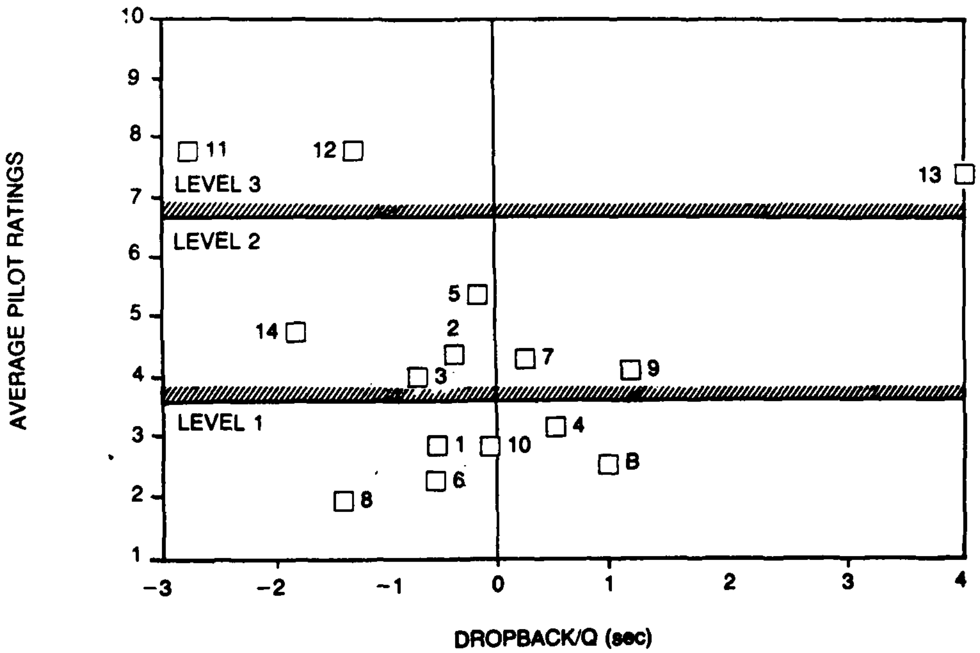


FIGURE 32 AVERAGE FLARED LANDING PILOT RATING vs DROPBACK/q

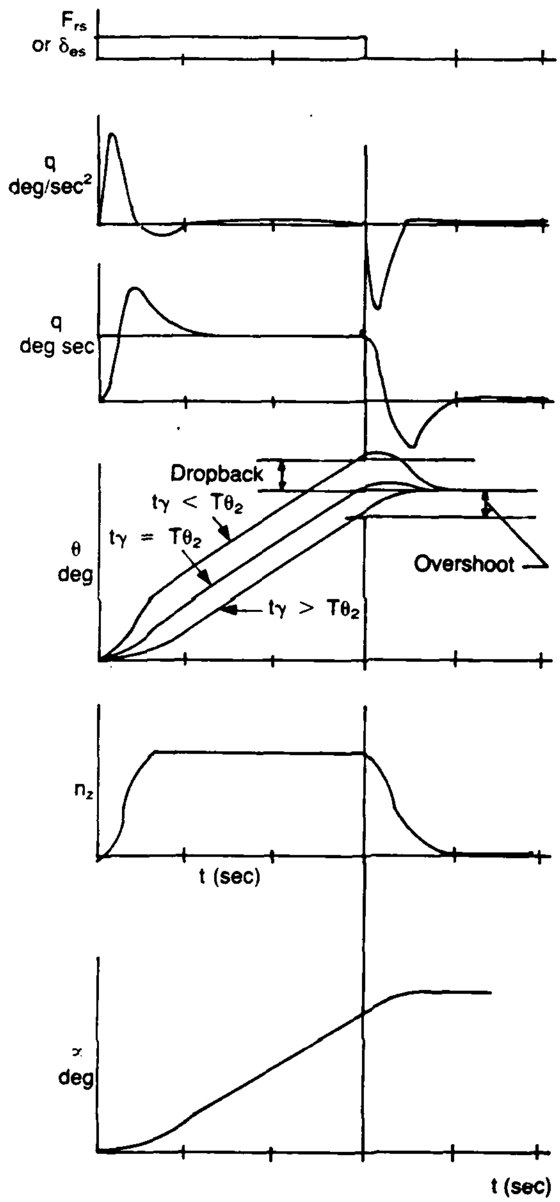


FIGURE 33 TYPICAL AIRCRAFT RESPONSES AS DEFINED BY GIBSON

Requirement (b) calls for the n_z step response to within the envelope shown in Figure 8. The envelope describes a well-damped first or second order response as a function of minimum and maximum short period irequency defined by n/α. (From MIL-F-8785C Category A requirements: $\omega_{n_{min}} = 0.55 \sqrt{n/\alpha}$, $\omega_{n_{max}} = 1.95 \sqrt{n/\alpha}$) Figure 34 shows the normalized time history response for configuration 7 to a step input and the corresponding envelope. The remaining cases are in Appendix D.3.

Considering Level 1 handling qualities to be those cases which satisfy the n_z time history envelope, 47% of the configurations corresponded with this requirement for the approach task and 60% for the flared landing task. Again since not all the configurations had similar time histories as those shown in Figure 33, the n_z response envelope did not accurately describe all the configurations and their expected handling qualities. Configurations 1, 2, 3, 4, and 13 displayed an initial overshoot and then dropped back toward zero and in some cases even reversed response (configurations 1, 4 and 13). Not all of these cases were rated worse than Level 1. Configurations 1, 2 and 13 were rated as Level 1 for the approach task and for the flared landing task configurations 1 and 4 were rated Level 1. The baseline configuration had a ramp-like n_z response and was rated as Level 1 for both the approach and flared landing tasks.

The approach and landing results for the second part of requirement (b) are shown in Figure 35. The figure shows a plot of τ_{n_z} vs n/α where τ_{n_z} was defined as a function of damping and short period frequency derived from MIL-F-8785C Category A CAP requirements. For the cases which did not have a second order response, τ_{n_z} was defined by this author as the time to reach 95% of the peak overshoot. For the approach task 53% of the cases corresponded with the average pilot ratings while for the flared landing task 40% corresponded with the average pilot ratings.

Requirement (c) states that the frequency response of the θ/F_S transfer function should fall within the envelope shown in Figure 10 with the gains of the θ/F_S transfer functions adjusted so that the crossover is at −120 degrees of phase. The frequency at −120 degrees of phase was also required to be between 0.25 and .5 Hz. The frequency response plot for configuration 7 is shown in Figure 36. The remaining plots are in Appendix D.4.

It was considered that the cases which fell within the optimum attitude response envelope would be representative of Level 1 handling qualities and those outside the envelope were not Level 1. The combined envelope and frequency requirements were able to correlate with 53% of the average approach pilot ratings and 67% of the average flared landing pilot ratings.

Thus far the requirements have been used to determine whether the aircraft configurations were satisfactory (Level 1) or not satisfactory (Levels 2 or 3). Attempts were made to establish the Level 2 or 3 boundaries by considering the frequency values at −120 degrees phase and the corresponding pilot ratings. Figures 37 and 38 show the results for the approach and flared landing tasks. There is a trend of increasing pilot ratings with decreasing values for ω_{120} for both tasks. This is indicated by the bands drawn. As can be seen in Figure 37 the pilot ratings were between 2 and 4 Cooper-Harper Handling Qualities Ratings for the range of .16 to .31 Hz. This does not allow for a clear separation between the Level 1 and 2 configurations. It also indicates that for the approach task the frequency at −120 degrees of phase may not contribute to the prediction of handling qualities levels or may not even be necessary as a requirement for the frequency response envelope. If only the θ/F_s response envelope was considered, the same results occur with or without the frequency requirement.

In Figure 38 a more definite trend can be seen between the various handling qualities levels for the flared landing task. Determining frequency values to define the separate handling qualities levels could not be done due to the scatter of the data.

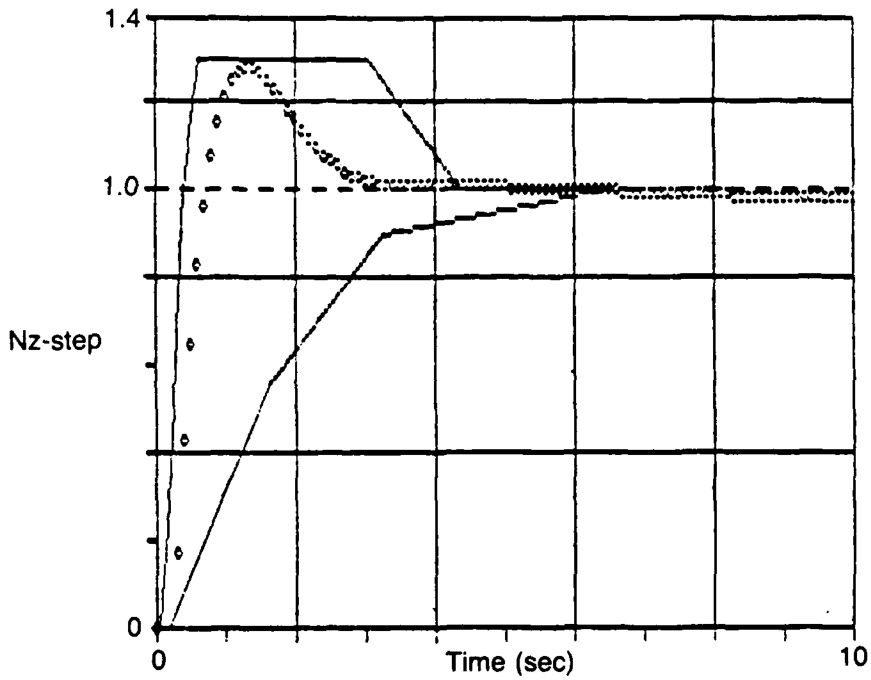
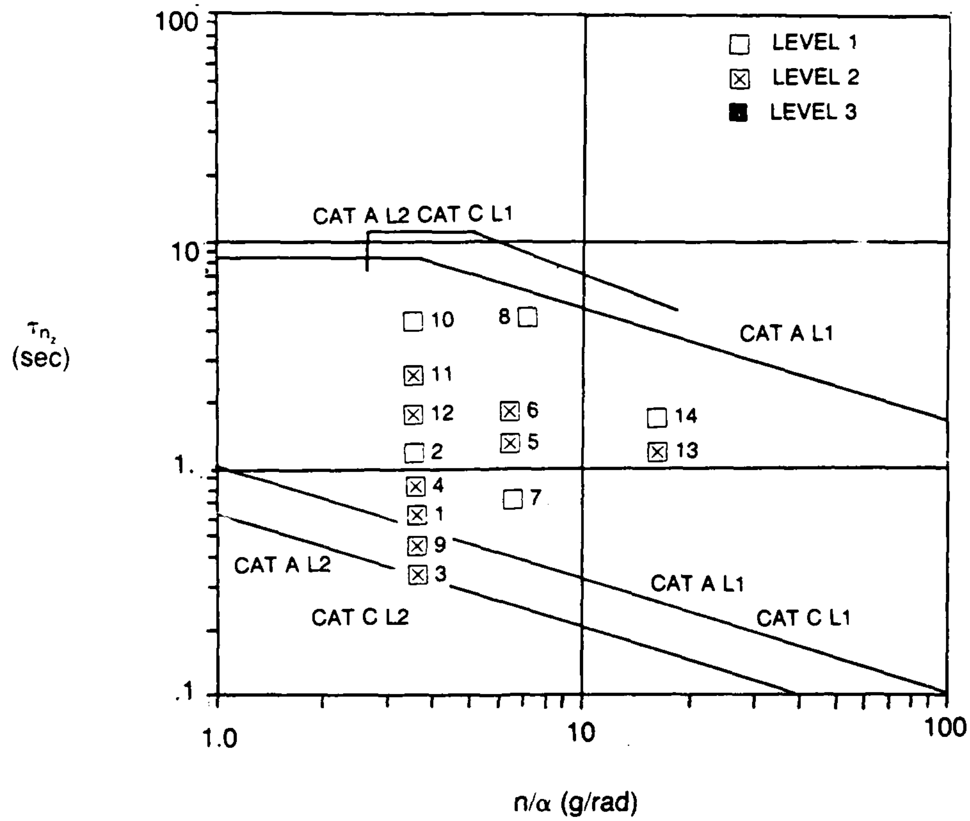
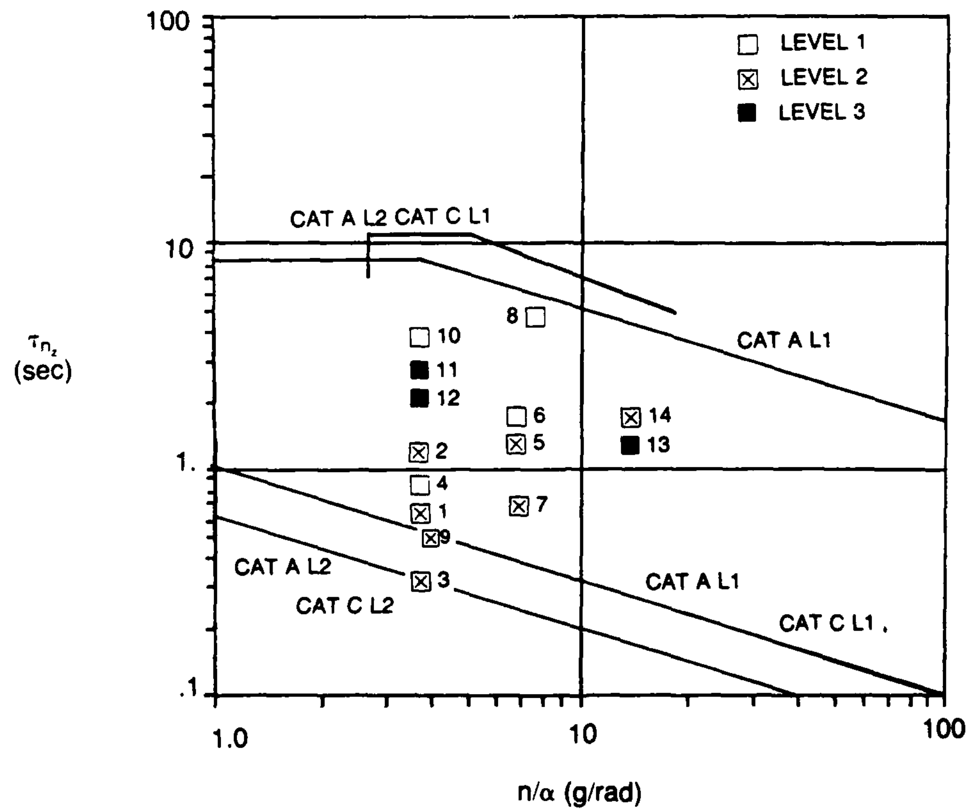


FIGURE 34 NORMALIZED n_z RESPONSE — CONFIGURATION 7



APPROACH



FLARED LANDING

FIGURE 35 τ_{n_z} vs n/α — APPROACH AND FLARED LANDING RESULTS

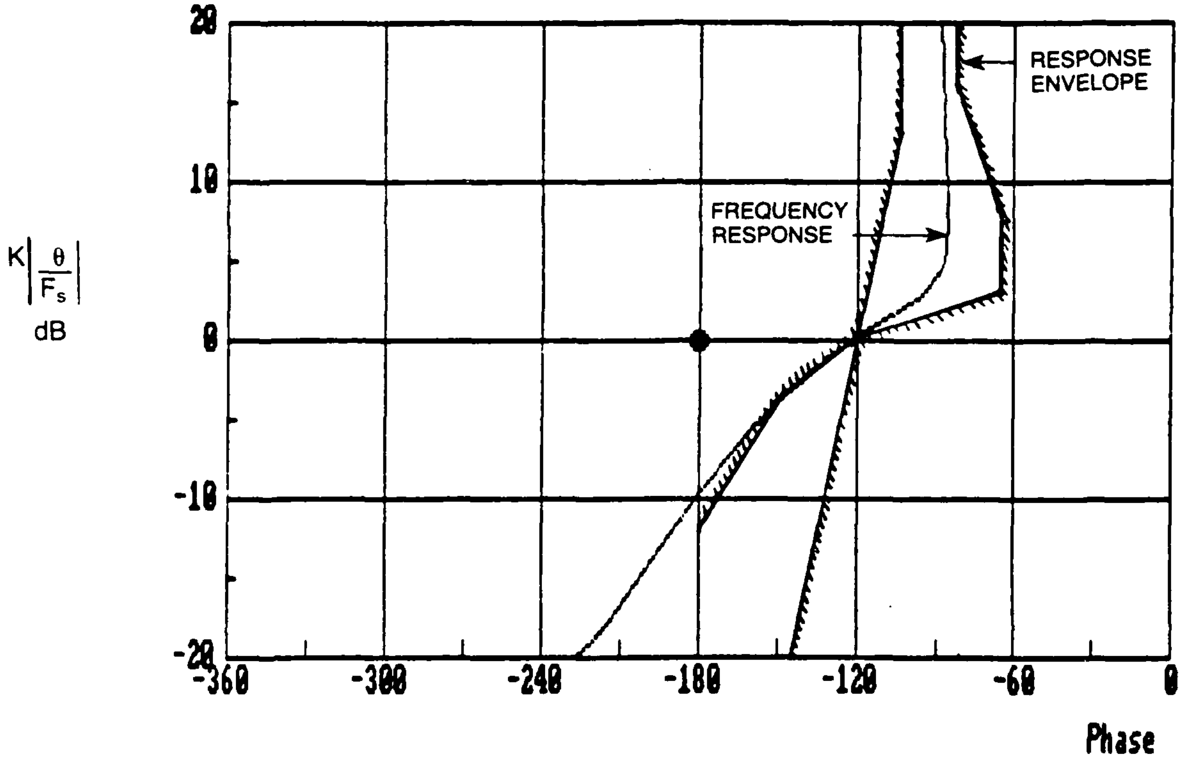


FIGURE 36 OPTIMUM ATTITUDE BOUNDARIES — CONFIGURATION 7

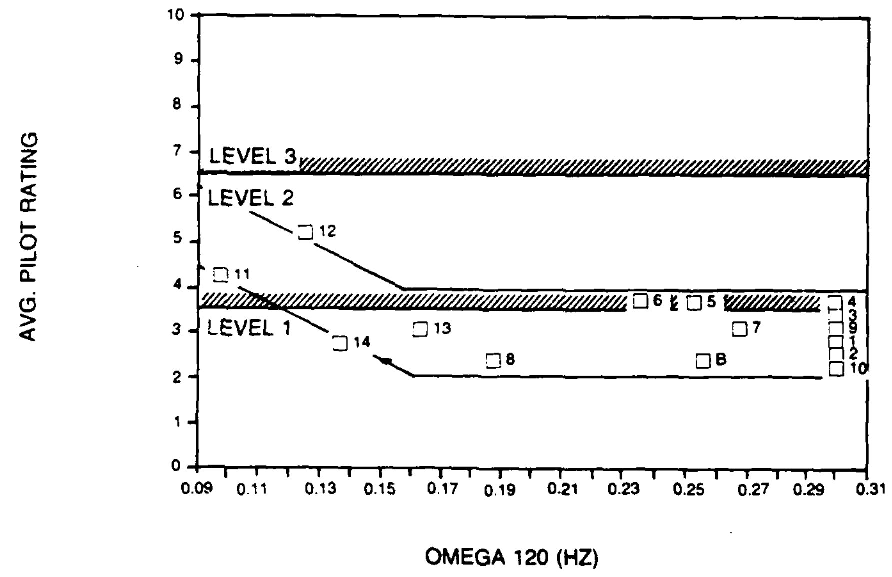


FIGURE 37 AVERAGE APPROACH PILOT RATINGS vs ω_{120}

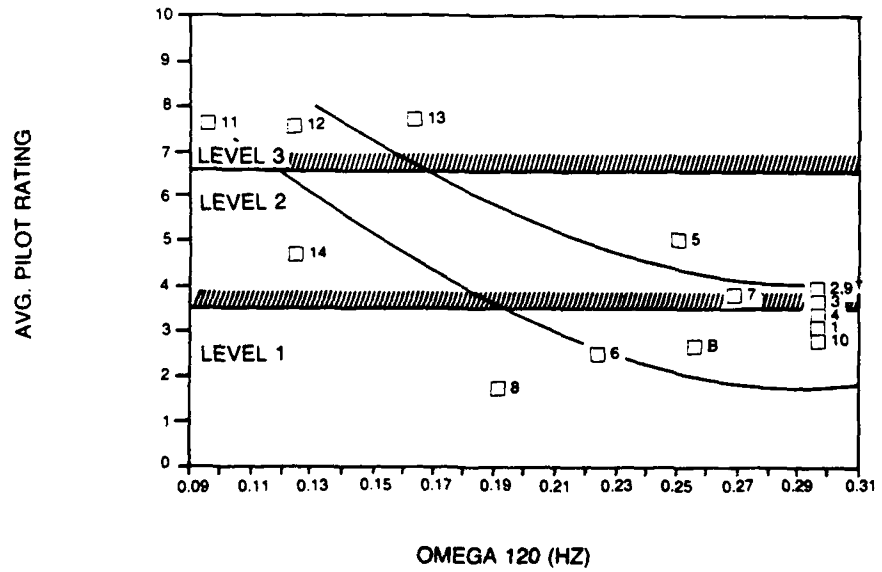


FIGURE 38 AVERAGE FLARED LANDING PILOT RATINGS vs ω_{120}

Gibson had mentioned in reference d that the frequency at -180 degrees (ω_{180}) was to be 1 Hz or greater. Applying this requirement to the approach task reduced the correlation with pilot ratings to 47% and the flared landing task correlation was reduced to 60%. The frequency values at -180 degrees phase were plotted against the approach and flared landing task pilot ratings in Figures 39 and 40.

The trend for the approach task that occurred in Figure 37 also occurred in Figure 39 for ω_{180}. Again the frequency response envelope provided better indication as to whether the configuration would be rated Level 1 or not for the approach task. It is possible that neither set of frequency values may have contributed to the pilot evaluations. Similarly in the bandwidth, time delay criterion, the bandwidth values could not separate the Level 1 and 2 configurations for the frequency range of .9 to 3.3 rad/sec. Contributing to the difficulty of separating Level 1 from Level 2 configurations was that most of the average approach ratings were between 2 and 4.

For the flared landing task results in Figure 40 it can be seen that there is less scatter between the data points than there was in Figure 38. Also a clearer separation between the frequency values and the corresponding level ratings can be seen by the dashed lines drawn. If the separations shown are used in conjunction with the frequency response envelope, then 73% of the cases correlated with the average pilot ratings by level. Some improvement was shown for the flared landing task using ω_{180} as a parameter, but further investigation is necessary.

The last requirement noted in Gibson's criteria was that the frequency response must satisfy the gain attenuation (Gain $\theta/F_s \leq 0.1$ deg/lb) and phase lag rate of increase (phase rate ≤ 100 deg/H_z) at the crossover frequency. Using these requirements 60% of the approach cases corresponded with the average pilot ratings and 80% of the flared landing cases corresponded with the average pilot ratings. The phase rate and gain attenuation were plotted against the average approach and flared landing pilot rating to determine possible handling qualities levels.

Figures 41 and 42 show the average pilot ratings vs phase rate for the approach and flared landing tasks. It can be seen that for the approach task, the phase rate was between 77 and 136 deg/H_z (except for the $\dot{\gamma}$ configurations) with an average phase rate of 107 deg/H_z. In that range there was no clear separation between the Level 1 and 2 configurations, again due to the pilot ratings being between 2 and 4. From the trend lines drawn it can be seen that at higher phase rates (> 250 deg/H_z) the configurations were definitely Level 2. In Figure 42 a better separation can be seen between the flared landing cases rated as Level 1 and not Level 1 about the phase rate value of 100 deg/H_z; where for increasing phase rate there is a decrease in handling qualities. For this case there is some scatter of the data about the trend lines drawn with 80% of the cases within the bounds. From the trend lines drawn, phase rate level values were determined and corresponded with 73% of the average pilot ratings.

Figures 43 and 44 are plots of average pilot ratings vs crossover gain values for the approach and flared landing tasks. Requiring that the gain at the crossover frequency be less than 0.1 deg/lb provided 67% correlation with the average approach pilot rating and 53% correlation with the average flared landing pilot rating. For the approach case a definite trend of increasing handling quality rating with increasing gain attenuation values can be seen. Again for the approach task it is difficult to determine a value which would separate the Level 1 from Level 2 configurations. The limiting value of 0.1 gain attenuation at -180 degrees of phase was kept since a majority of the configurations satisfied this criteria. Combining the phase rate and gain attenuation results provided 53% correlation with the average pilot ratings.

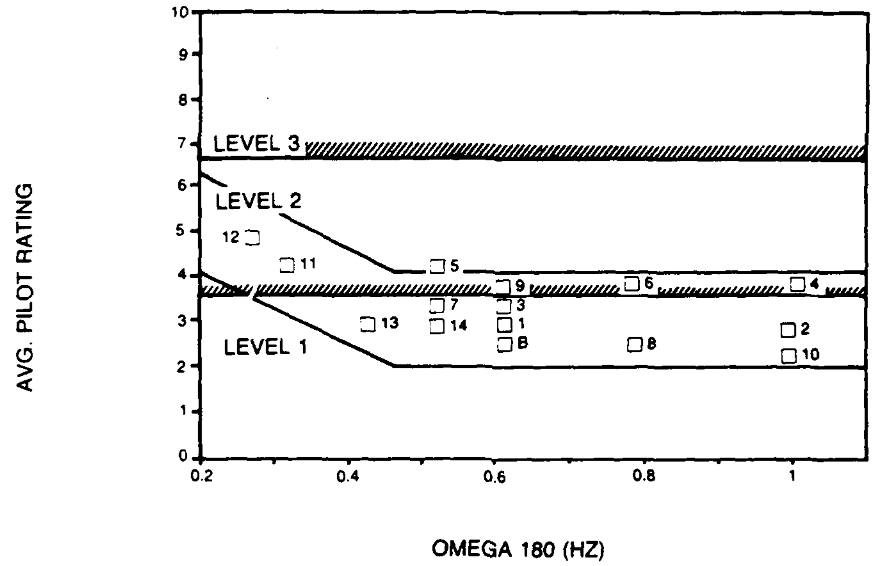


FIGURE 39 AVERAGE APPROACH PILOT RATINGS vs ω_{180}

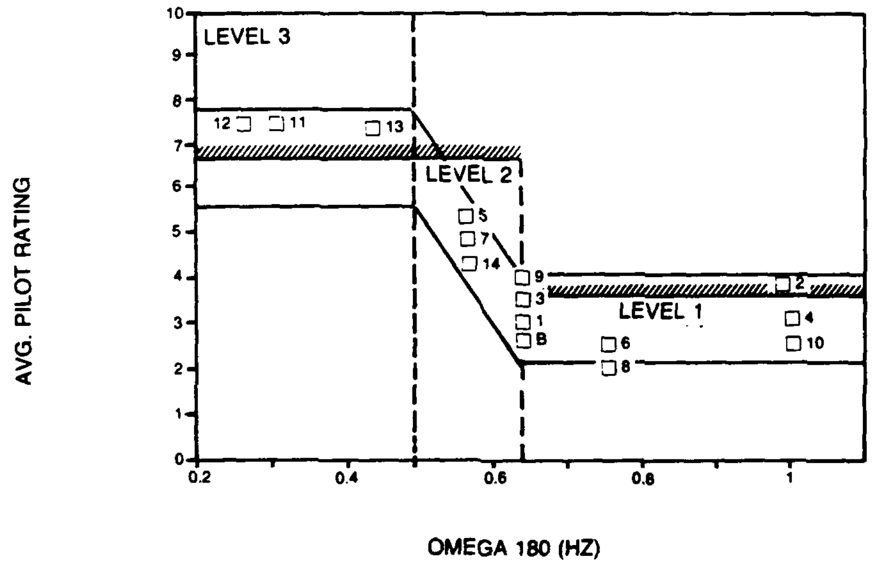


FIGURE 40 AVERAGE FLARED LANDING PILOT RATINGS vs ω_{180}

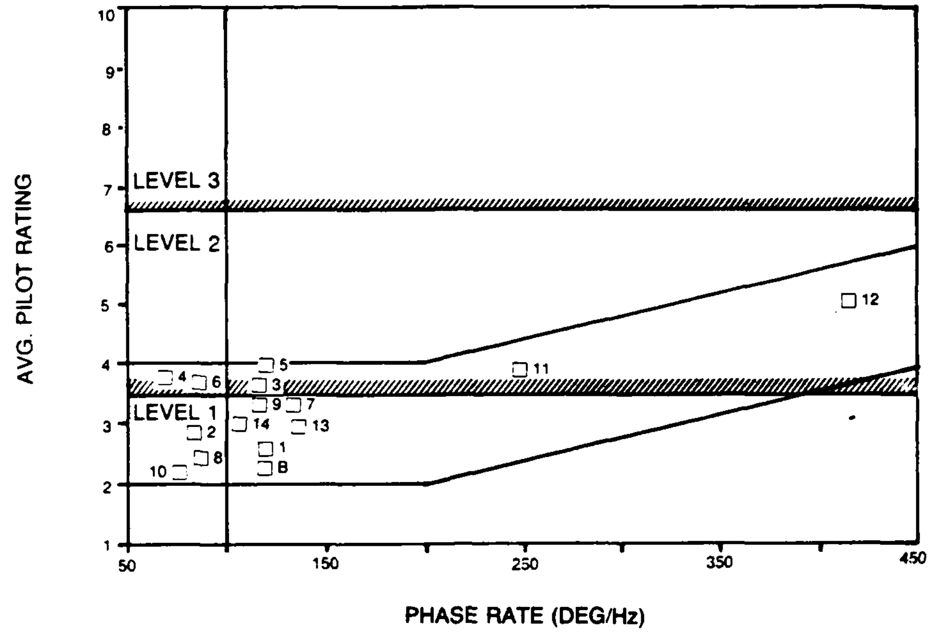


FIGURE 41 AVERAGE APPROACH PILOT RATINGS vs PHASE RATE

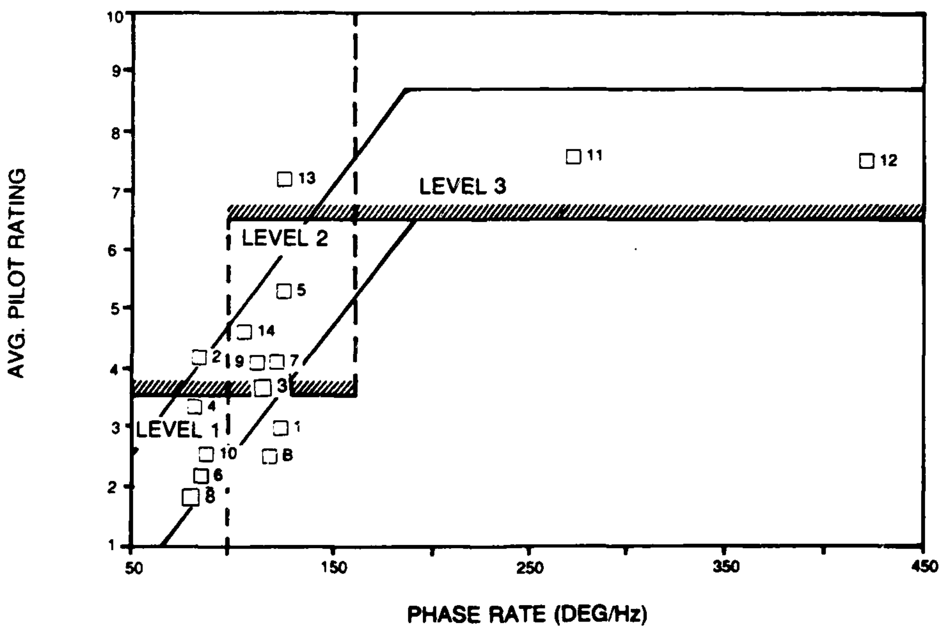


FIGURE 42 AVERAGE FLARED LANDING PILOT RATINGS vs PHASE RATE

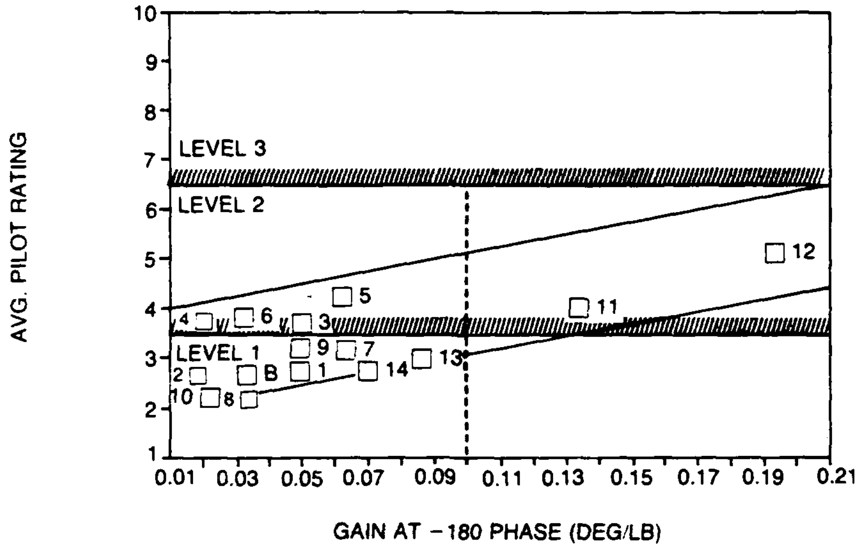


FIGURE 43 AVERAGE APPROACH PILOT RATINGS vs CROSSOVER GAIN

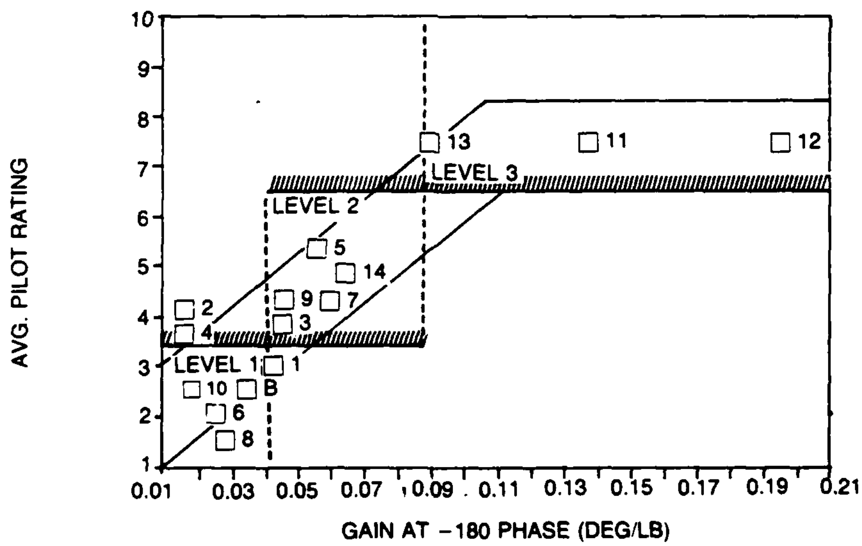


FIGURE 44 AVERAGE FLARED LANDING PILOT RATINGS vs CROSSOVER GAIN

It can be seen that for the flared landing case, with increasing gain attenuation values there were increased handling qualities ratings. The configurations seemed to separate by level into the boundaries shown with the dashed lines. These lines provide 93% correlation by level with the average pilot ratings. Combining the new gain attenuation boundaries with the phase rate requirement again resulted in 80% correlation by level with the average flared landing pilot rating.

Combinations of the four requirements were considered but the best results occurred if only requirement (d) was applied. There still is a need for better criterion to predict approach short period handling qualities.

2.6 ANGLE OF ATTACK TIME HISTORY ENVELOPE

From the NASA/Calspan study (reference b) it was noted that the data base used to develop the angle of attack time history envelope was from a variable stability aircraft generally configured as an angle of attack or conventional command system with stable but lightly damped phugoid modes. As described in the Introduction, the type of command system determines the general shape of the aircraft responses. Therefore this envelope was not applicable to the pitch rate or $\dot{\gamma}$ command systems. Another limitation noted about the data base was that the phugoid effects were not specifically documented so only those configurations without phugoid mode residuals could be evaluated with respect to the envelope. Of the 15 configurations, 6 could be evaluated with respect to the angle of attack time history envelope. The configurations were 1, 4, 5, 8, 9 and 13.

Figures 45 through 48 show the angle of attack response with respect to the time history envelope criteria. Table 7 lists the predicted flying qualities and the average pilot ratings for the approach and flared landing tasks. From Figure 47 and Table 7 it can be seen that configurations 5, 9 and 13 had the same angle of attack response but different average pilot ratings for the flared landing task. Note the envelope predicted the flying qualities to be Level 1 but configurations 5 and 9 were rated Level 2 for the approach and flared landing tasks. Configuration 13 was correctly predicted as Level 1 for the approach task. The envelope did not correspond with the Level 3 rating configuration 13 received for the flared landing task.

Of the six applicable configurations only 3 (configurations 1, 4 and 13) corresponded with the average pilot rating for the approach task and configuration 1 was the only case to correspond with the flared landing pilot ratings. This criteria provided the worst correlation with the average pilot ratings for the set of configurations used in this study. Of the 15 configurations, only 20% of the configurations corresponded with the average approach pilot ratings and 6.7% corresponded with the average flared landing pilot ratings.

TABLE 7 ANGLE OF ATTACK TIME HISTORY RESULTS

CONFIG.	PRED. F.Q.LEVEL	AVG. APPROACH HQR	AVG. FLARED LANDING HQR
1	1	2.75	2.88
4	$\neq 1$	3.75	3.25
5	1	4.0	5.0
8	$\neq 1$	2.33	2.0
9	1	3.5	4.0
13	1	3.0	7.25

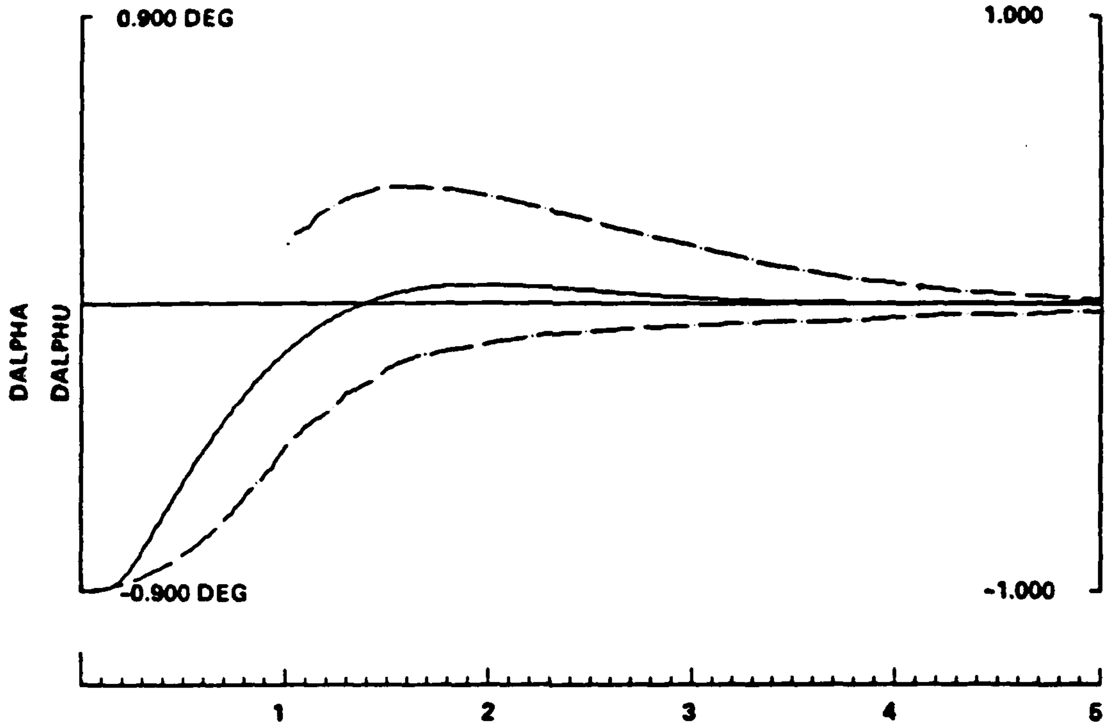


FIGURE 45 NORMALIZED ANGLE OF ATTACK RESPONSE — CONFIGURATION 1 (reference b)

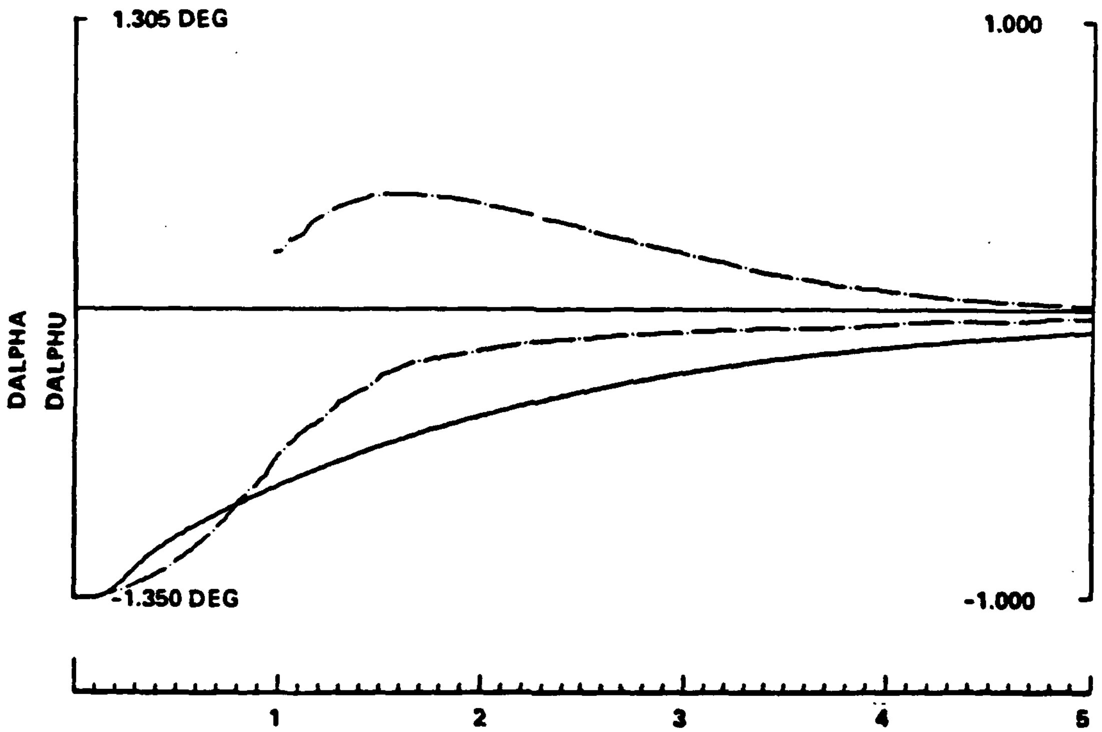


FIGURE 46 NORMALIZED ANGLE OF ATTACK RESPONSE — CONFIGURATION 4 (reference b)

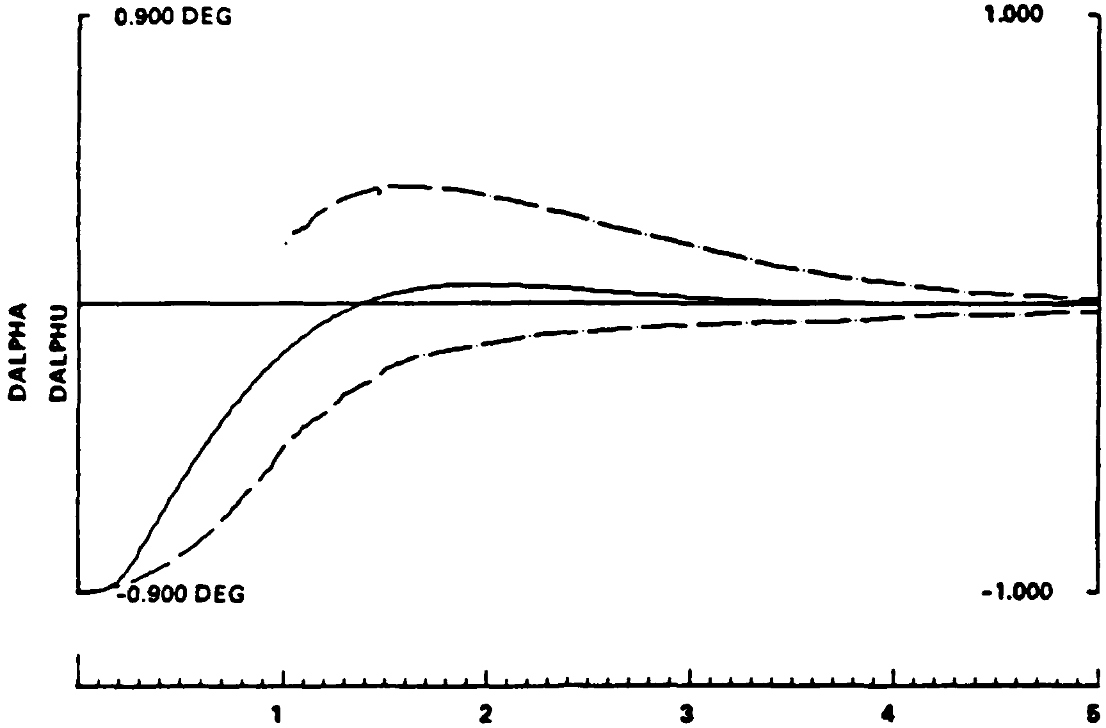


FIGURE 47 NORMALIZED ANGLE OF ATTACK RESPONSE — CONFIGURATIONS 5, 9, 13 (reference b)

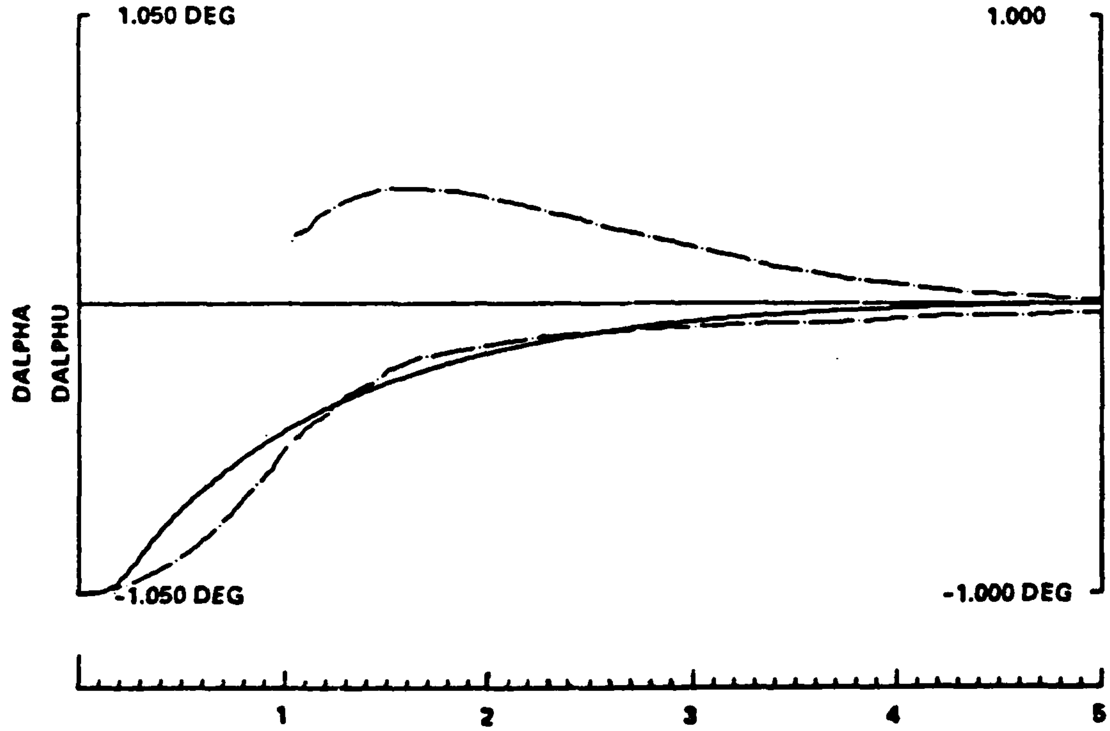


FIGURE 48 NORMALIZED ANGLE OF ATTACK RESPONSE — CONFIGURATION 8 (reference b)

2.7 TIME DOMAIN CRITERIA

The predictive criteria was defined in reference b as follows:

$$PHQR' = 1.7\dot{\alpha}' - 1.44N_{z_p}' + 0.55T\dot{\alpha} + TD' + \dot{q}' + 2.0$$

The 2.0 is a bias term where a "criteria perfect" ($\dot{\alpha}' = N_{z_p}' = T\dot{\alpha} = TD' = \dot{q}' = 0$) would yield an PHQR' of 2. All other terms are as previously defined in the introduction.

There are several limitations to this criteria.

1. The criteria is applicable *only* to the flared landing task for large transport aircraft.

2. Pitch controllers other than wheel and center stick (side stick for example) are not applicable due to lack of sensitivity data. It was stated in the report that the sensitivity parameters for the center stick have not been sufficiently defined.

3. Lightly damped configurations were not applicable. The criteria was designed to allow the flight control designer to locate poles and zeros to satisfy Level 1 boundaries of MIL-F-8785C $\omega_{n_{sp}}$ vs n/α requirements. Thus lightly damped configurations were not applicable as well as excessively low or high frequencies.

4. Divergent configurations also were not applicable by the same reasoning as the lightly damped cases.

5. "Decoupled" configurations such as 9 and 10 were not applicable since they showed flat steady state responses for both the q and α response. This was a result of the use of direct lift flaps and these effects were not included in the development of the predictive handling qualities criteria.

Table 8 lists the values used to develop the predictive handling qualities ratings for the cases considered in this study. Figure 49 shows the average handling qualities ratings vs the predicted handling qualities ratings for the flared landing task. The results show an 80% correlation by level with the average handling qualities ratings.

Though this criteria seems to provide very good predictive capabilities it is limited to the flared landing task for transports with wheel pitch controls. This predictive technique seems highly dependent on task and type of aircraft (stable, conventional designs). To eventually develop predictive capabilities for all types of aircraft and tasks may require an excessive amount of flight testing and analysis. Each task or novel aircraft configuration may require the development of its own predictive equation.

2.8 SUMMARY

2.8.1 MIL-HANDBOOK SHORT PERIOD CRITERIA

Table 9 shows a comparison of the Mil-Handbook recommended short period criteria and their correlation with the approach and flared landing pilot ratings. The best correlation for both the approach and flared landing task was part d from Gibson's criteria. The Handbook states that this criteria was "intended for fly-by-wire control law design optimization and overall handling Levels 1, 2 and 3 have not been established." Attempts have been made to determine handling qualities levels in this study but further investigation would be necessary for inclusion in a Standard.

TABLE 8 TIME DOMAIN CRITERIA APPLICATION
($PHQR' = 1.7\dot{\alpha}' - 1.44N_{\dot{z}_p} + 0.55T\dot{\alpha} + TD' + \dot{q}' + 2.0$)
(where TD' and $\dot{q}'$ used wheel sensitivity factors)

CONFIG	$1.7\dot{\alpha}'$	$-1.44N_{\dot{z}_p}$	$0.55T\dot{\alpha}$	TDq	TD	$\dot{q}$	PHQR'	AHQR
1	0	0	0.11	160	1.33	.25	3.69	2.9
2	0.49	0	0	150	1.11	.25	3.85	4.0
3	0.17	0	0	160	1.33	.25	3.75	3.7
4	0.19	0	0	140	0.89	.25	3.33	3.3
5	0	0	0	160	1.33	.25	3.58	5.0
6	0	0	0	150	1.11	.25	3.36	2.3
7	0	0	0	160	1.33	.25	3.58	4.0
8	0.07	0	0.10	150	1.11	.25	3.53	2.0
9	0	0	0	160	1.33	.25	3.58	4.0
10	0.15	0	0	150	1.11	.25	3.51	2.8
11	1.0	0	33	250	3.33	.25	9.88	7.5
12	0.85	0	33	290	4.22	.25	10.62	7.5
13	0	0	0	160	1.33	.25	3.58	7.3
14	0.34	0	0	160	1.33	.25	3.92	4.5
B	0	−0.58	0	150	1.11	.15	2.7	2.6

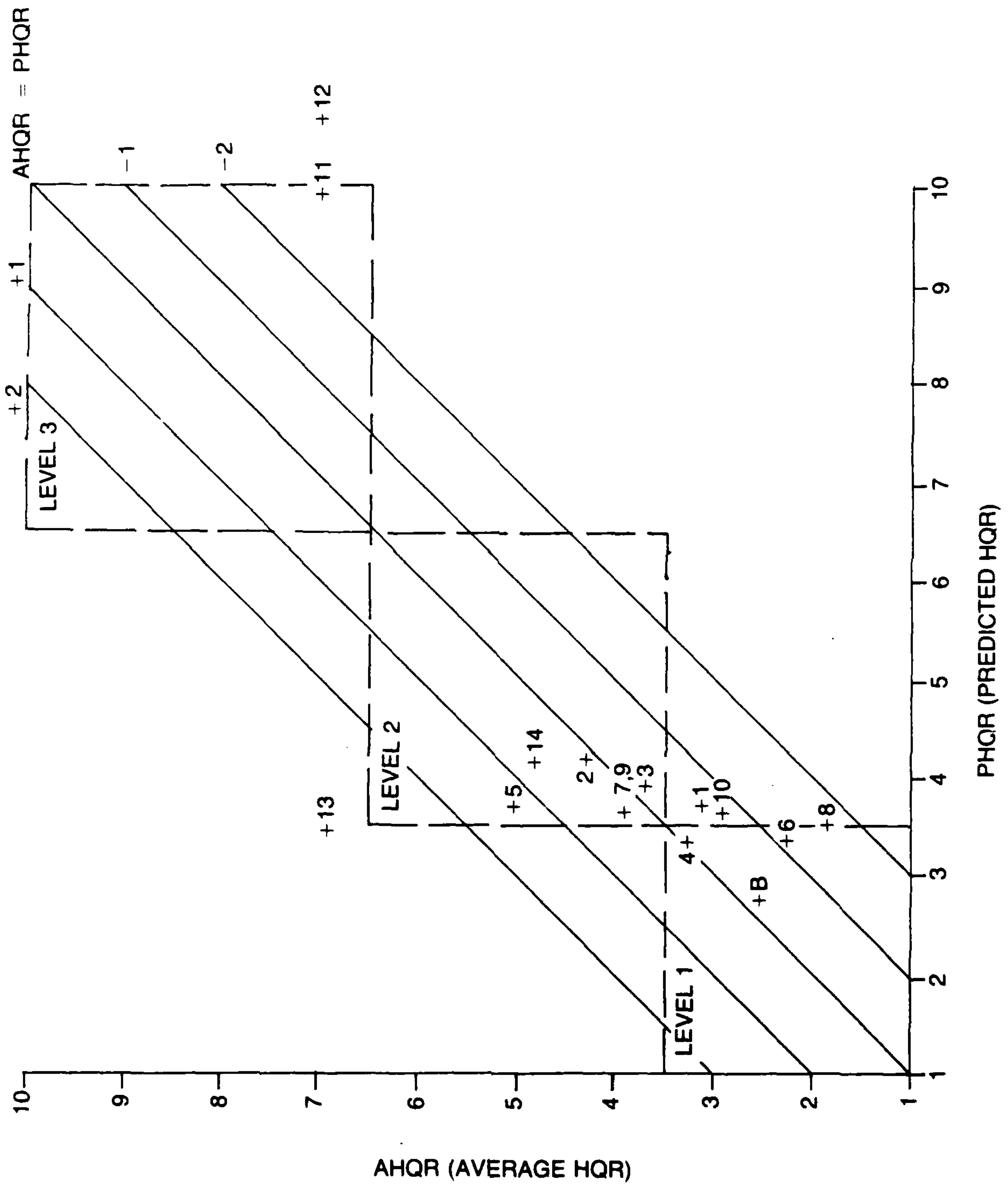


FIGURE 49 TIME DOMAIN CRITERIA RESULTS FOR THE FLARED LANDING TASK

TABLE 9 COMPARISON OF MIL-PRIME HANDBOOK CRITERIA

CRITERIA		PERCENT CORRELATION WITH AVERAGE PILOT RATINGS: APPROACH	PERCENT CORRELATION WITH AVERAGE PILOT RATINGS: FLARED LANDING
MIL-F-8785C	CAT A	53 (q and n_{z_p} equiv. system match)	(2 part α then q match)
ω_{sp} vs n/α, ζ_{sp}	CAT C	47 (q and n_{z_p} equiv. system match)	47 (q only equiv. system match – $1/T_{\theta_2}$ Free)
			40 (q only equiv. system match – $1/T_{\theta_2}$ Free)
CAP vs ζ_{sp}	CAT A	47 (q and n_{z_p} equiv. system match)	47 (2 part α then q match)
CAP vs ζ_{sp}	CAT C	53 (q and n_{z_p} equiv. system match)	47 (2 part α then q match)
$\omega_{sp}T_{\theta_2}$ vs ζ_{sp}	CAT A	47 (q and n_{z_p} equiv. system match)	40 (q only equiv. system match – $1/T_{\theta_2}$ Free)
$\omega_{sp}T_{\theta_2}$ vs ζ_{sp}	CAT C	53 (q and n_{z_p} equiv. system match)	30 (q only equiv. system match – $1/T_{\theta_2}$ Free)
TRANSIENT PEAK RATIO, RISE TIME, EFFECTIVE DELAY		53	47
BANDWIDTH	CAT A	20	60
BANDWIDTH	CAT C	40	53
CLOSED-LOOP		53	33
GIBSON'S ATTITUDE DROPBACK		53	47
t_{n_z} TIME HISTORY		47	60
t_{n_z} vs n/α		40	53
ATTITUDE FREQ. RESPONSE		53	67
ATTITUDE GAIN ATTENUATION AND PHASE RATE		60	80

None of the remaining criteria could adequately correspond with the pilot evaluations for either the approach or flared landing tasks. All but the bandwidth criterion yielded 53% correlation with the average approach pilot ratings. The bandwidth criterion seemed more applicable for the more demanding flared landing task — 60% correlation with the average pilot ratings using Category A requirements. In general the Category A requirements yielded slightly better correlation with the flared landing pilot evaluations than the Category C requirements.

Since all but the bandwidth criterion yielded the same results for the approach task, any of the remaining five criteria could be used in the development of the Standard for the approach task for a transport aircraft. The transient peak, rise time, effective delay criterion may be the best to include in a Standard, especially for an aircraft with higher order dynamics. The transient peak ratio, rise time, effective delay criterion does not require an equivalent system reduction. Thus there is no doubt as to whether the "proper" equivalent system match technique has been applied. It does not require the a pilot model as in the closed loop criterion. What the criterion does do is measure the relative effect of short period frequency, damping and time delay on the transient pitch rate response to a step input.

2.8.2 EQUIVALENT SYSTEMS TECHNIQUES

An attempt was made to determine if there was an equivalent system technique that best represented the aircraft configuration and provide a correlation with the applicable criteria recommended in the Handbook. The results were mixed, with three techniques giving the "best" correlation between pilot ratings and criteria requirements. The three methods were q/F_s match, the simultaneous q/F_s and n_{z_p}/F_s match and the two part α/F_s then q/F_s match.

For the approach task it was the q/F_s and n_{z_p}/F_s which gave the best results. Fixing or freeing $1/T_{\theta_2}$ generated the same results for the CAP vs ζ_{sp} and the $\omega_{sp}T_{\theta_2}$ vs ζ_{sp} criteria. Keeping $1/T_{\theta_2}$ fixed (at the airframe value) gave the best result for ω_{sp} vs n/α. Since the same results could be achieved with $1/T_{\theta_2}$ fixed or free, it would be best to do the simultaneous q/F_s and n_{z_p}/F_s match with $1/T_{\theta_2}$ fixed so as not to lose the significance of this term.

Both the two part α/F_s then q/F_s match and the q/F_s match with $1/T_{\theta_2}$ free generated the same results for Category A ω_{sp} vs n/α requirements. The two part match provided the best correlation between the flared landing pilot ratings and the CAP vs ζ_{sp} criteria. It was the q/F_s match which gave the best correlation for the $\omega_{sp}T_{\theta_2}$ vs ζ_{sp} criteria, but of all the equivalent system cases this showed the poorest correlation with the pilot evaluations for the remaining criteria.

2.8.3 TIME AND FREQUENCY RESPONSE BY GIBSON

On the whole, Gibson's criteria provided about the same percentage correlation with pilot rating for the approach task as the other criteria mentioned in the Handbook. Slightly better correlation with pilot rating was achieved for the flared landing task, indicating that Gibson's criterion may be more applicable to higher precision tasks.

As it was mentioned, part (d) of the criterion did provide the best correlation with the pilot ratings for both the approach and flared landing tasks. The Handbook, in discussing this criterion, indicated that the attitude dropback requirement would be a candidate for a new requirement. This may be true for other classes of aircraft, but for the transport type used in this study it was the gain attenuation and phase rate criterion that appeared to be a better candidate for a new criterion. Also definite trends were found to determine handling qualities levels based on gain attenuation values.

2.8.4 ALTERNATE CRITERIA

Alternate criteria as well as modifications to existing criteria were also considered in this study. The modifications were done so as to provide a better correlation with the given criteria based on the data used in this study.

Because all but one of the average approach pilot ratings were between 2 and 4 Cooper-Harper handling qualities ratings it was difficult to determine alternate boundaries for the approach task. The data tended to be either closely grouped together or widely separated without any clear separation between the Level 1 and 2 cases. This was evident by the equivalent or reduced results as seen in Table 10.

TABLE 10 COMPARISON OF ALTERNATE/MODIFIED CRITERIA

CRITERIA	PERCENT CORRELATION WITH AVERAGE PILOT RATINGS APPROACH		FLARED LANDING	
TRANSIENT PEAK RATIO CAT A	N/A		53	(+6%)
BANDWIDTH:				
TRANSPORT BOUNDARIES	33	(−7%)	73	(+17%)
MOD. TRANSPORT BOUNDARIES	N/A		80	(+20%)
CLOSED LOOP: PILOT GAIN vs PILOT PHASE	87		93	
GIBSON'S CRITERION:				
ATTITUDE FREQ RESP & ω_{180} VALUES	47	(−6%)	60	(−7%)
ATTITUDE FREQ. RESP & MOD. ω_{180} VALUES	N/A		73	(+6%)
α TIME HISTORY ENVELOPE	20		6.7	
PREDICTIVE TIME DOMAIN	N/A		80	

( ) *Improvement or Degradation from original requirements*

For the flared landing task there was some separation between the handling qualities levels which was reflected in the improved results. The only alternate criteria which showed no improvement was the angle of attack time history envelope. This criteria was by far the worst, primarily due to its limitations on the type of configurations which could be applied to the criteria. The best results for both the approach and flared landing tasks was from the pilot gain vs pilot phase criteria. The criteria compares the pilot gain and phase necessary to satisfy the closed-loop criteria. The boundaries were based solely on the results from this study which indicated that combinations of extreme (either large or small) phase and gain values would yield unsatisfactory handling qualities. Further investigation of this criteria is necessary.

Some of the modifications considered for the existing criteria were to apply Category A requirements in determining the rise time limits for the pitch rate time history criteria, apply transport boundaries (as determined in reference b) to the bandwidth criteria and considering the crossover frequency value in Gibson's frequency response envelope. Of the modifications to the existing criteria, the transport boundaries for the bandwidth criteria showed the best correlation to the flared landing pilot ratings. Further modifications to the transport boundaries slightly improved the results from 73% to 80% correlation with the average pilot ratings.

The time domain criteria also resulted in 80% correlation with average pilot ratings. Although it appears to be a very good candidate as a flying qualities criteria it was highly dependent on task and cannot be extended to other tasks or type of aircraft.

3.0 CONCLUSIONS

The primary short period criteria recommended in the MIL-PRIME Handbook could not satisfactorily predict the handling qualities for the 15 transport configurations used in this study. The gain attenuation and phase rate criterion from Gibson's criterion provided the best correlation with the pilot evaluations in predicting the Level 1 and non-Level 1 configurations, especially for the flared landing task. More research is necessary to determine boundaries for the handling qualities levels. Initial results from this study indicate that the gain attenuation values at the crossover frequency may be used to determine handling qualities levels.

Using Category A requirements to predict the flared landing handling qualities showed a slight improvement over Category C requirements. This indicates that the stricter requirements may be more applicable to the flared landing task, but further consideration is necessary.

None of the equivalent system techniques applied in this study could generate equivalent transfer functions which satisfactorily correlated with the pilot ratings. A much simpler and less time consuming criteria was the transient peak ratio, rise time, effective delay criteria. This technique provided the same results as the "best" equivalent system match while still measuring the same parameters — effective frequency, damping and time delay.

During attempts to better understand the existing criteria the values for the pilot gain and phase necessary to satisfy the closed loop criteria were examined. The results from the configurations used in this study indicated that there were possible boundaries on the values of the gain and phase necessary to satisfy the closed-loop requirements. Further investigation is necessary, but it does show promise either as candidate criteria or potential limits for the pilot models used in the closed-loop criterion.

4.0 RECOMMENDATIONS

The results show that there was no established criteria which would be most applicable for the inclusion in a Standard for present and future Navy transports. No criterion could completely correlate with the pilot ratings used in this study. The gain attenuation and phase rate criterion from Gibson's criterion seems promising. Further investigation of this criterion should be done to determine level boundaries as well as its applicability to other tasks and vehicle classes. The pilot phase and gain value boundaries determined in this study should also be investigated since the boundaries were based only on the configurations used in this study.

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d. Gibson, John C., "Piloted Handling Qualities Design Criteria for High Order Flight Control Systems", AGARD-CP-333, June 1982.

e. Gibson, John C., "Handling Capabilities for Unstable Combat Aircraft", ICAS-86-5.3.4, Sep 1986.

f. Hodgkinson, J., Givan, M.E., and LaManna, W.J., "Longitudinal Short Period Equivalent System Frequency Curve Fit", McDonnell Douglas Corp. Computer Program LONGFIT, 25 Oct 1978.

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i. Background Information and User Guide for MIL-F-8785B (ASG): "Military Specification — Flying Qualities of Piloted Airplanes", AFFDC-TR-69-72, Aug 1969.

j. Hale, Francis J., "*Introduction to Control System Analysis and Design*", Prentice-Hall, Inc, Englewood Cliffs, New Jersey, 1973.

APPENDIX A

This appendix presents the time and frequency responses for the 15 configurations used in this study. The time histories are for a 10 lb step input. The responses presented are:

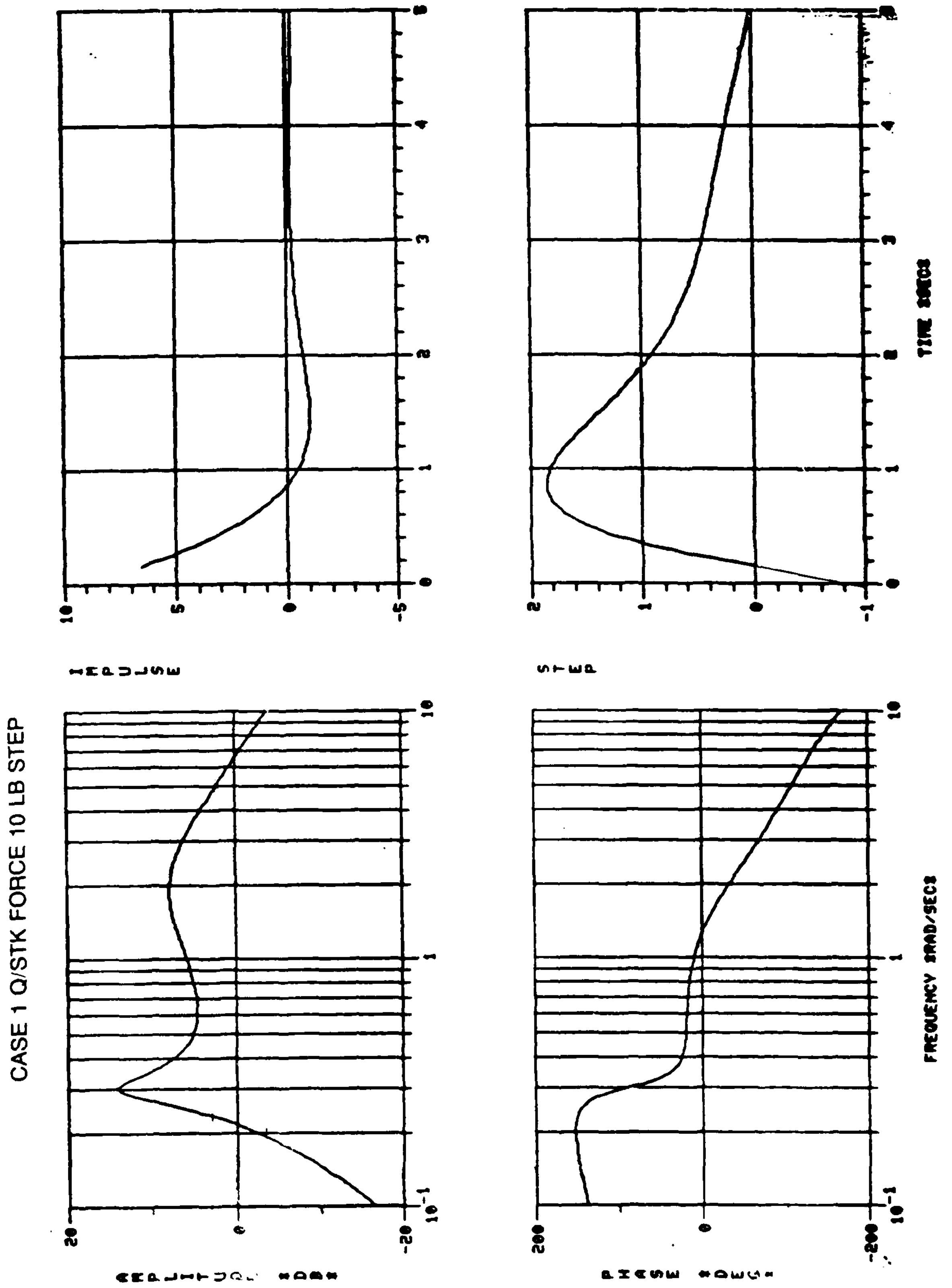
pitch rate (Q)

pitch attitude (THETA)

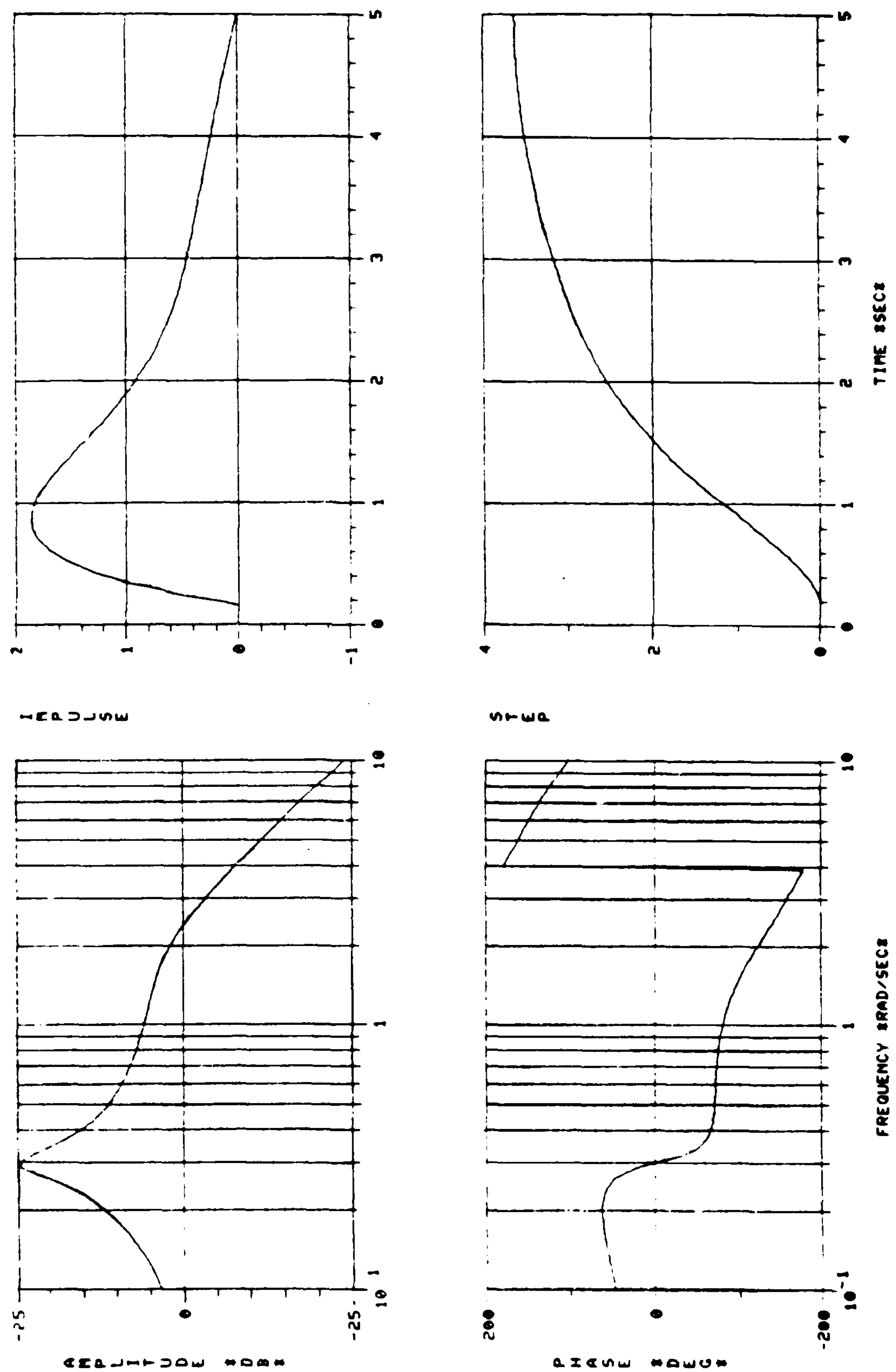
angle of attack (ALFA)

normal acceleration at the pilot station (NZP)

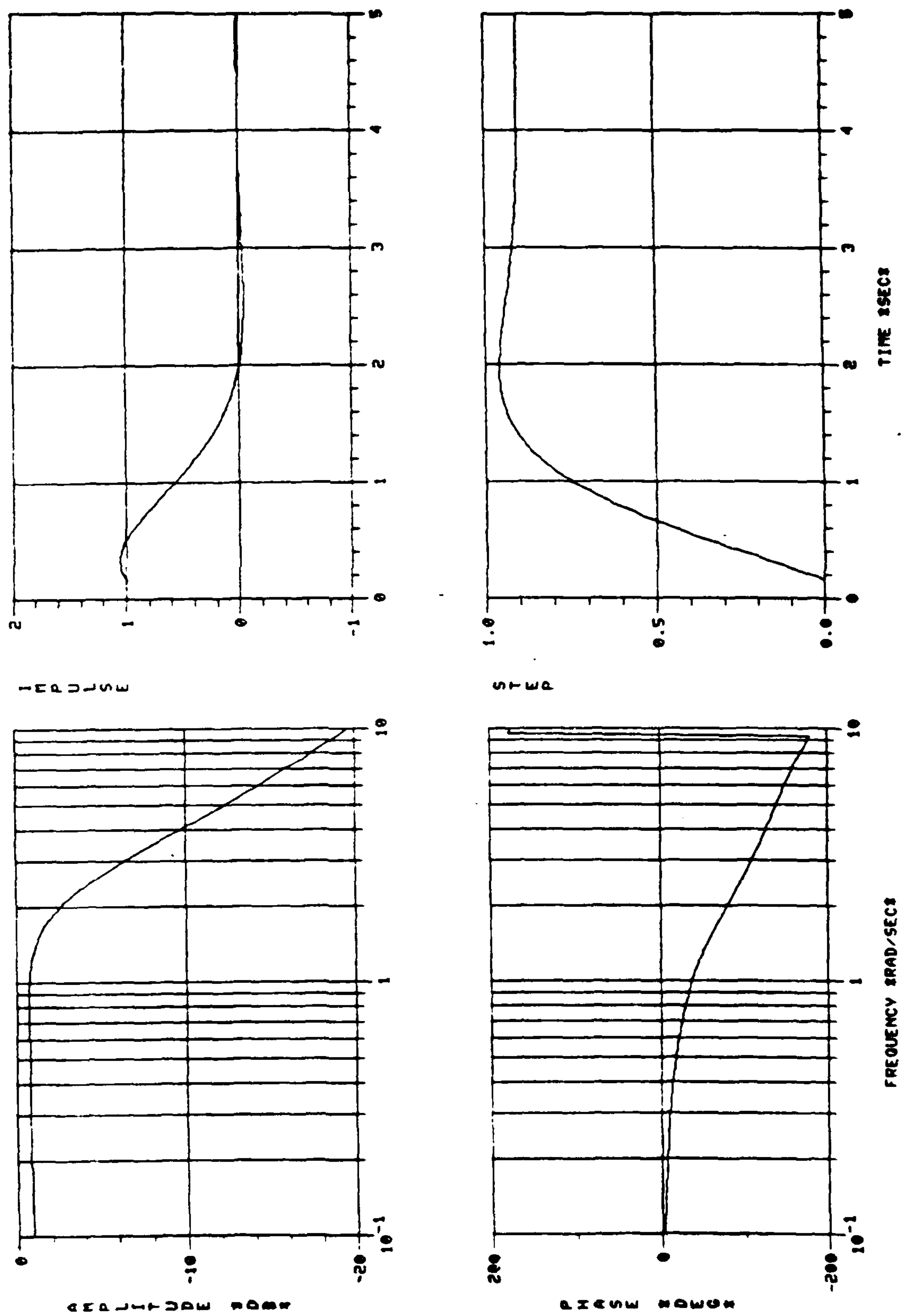
normal acceleration at the c.g. (NZCG)


CASE 1 Q/STK FORCE 10 LB STEP
TIME SECS
FREQUENCY RAD/SECS

CASE 1 THETA/STK FORCE 10 LB STEP



CASE 1 ALFA/STK FORCE 10 LB STEP



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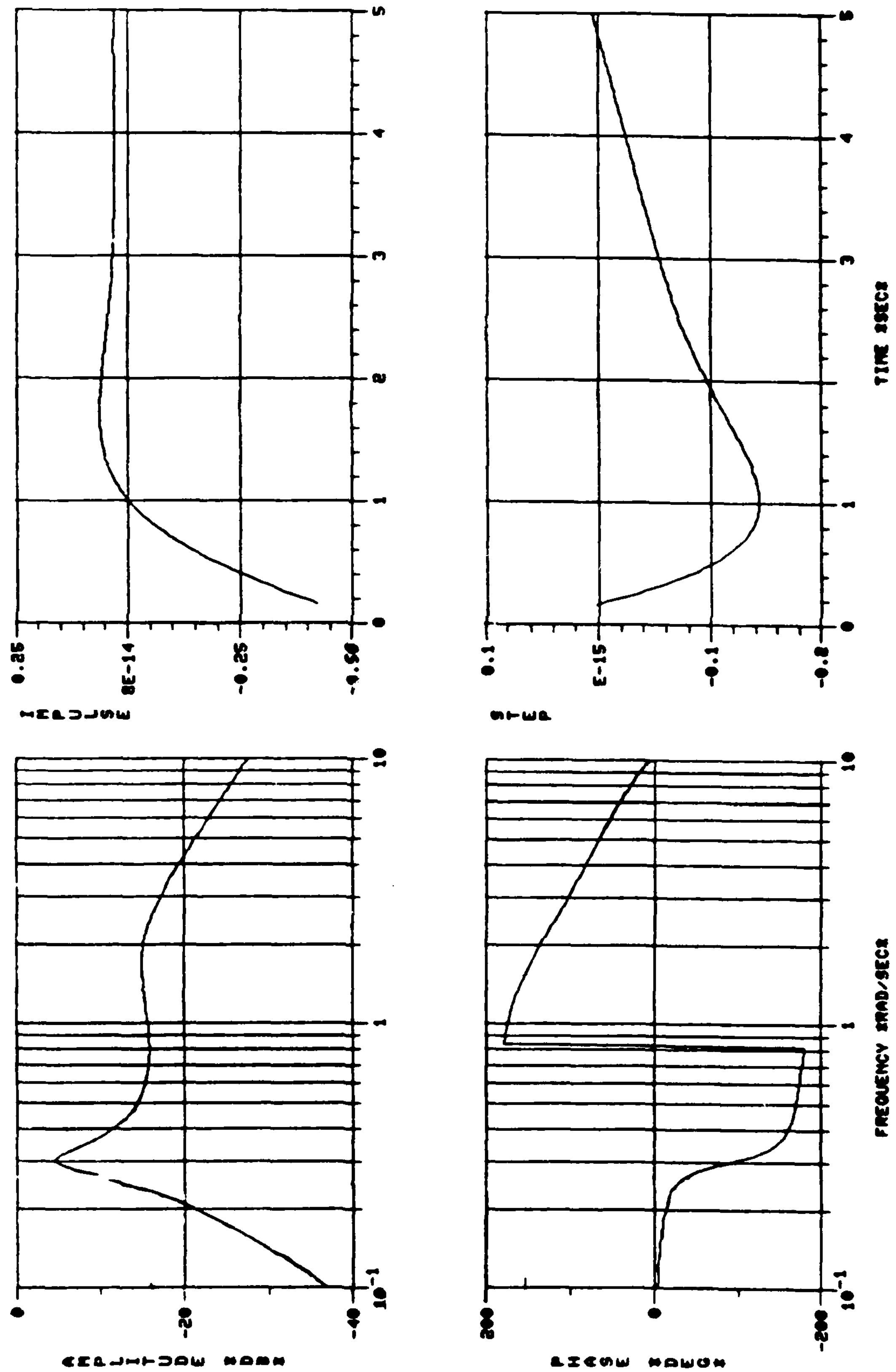

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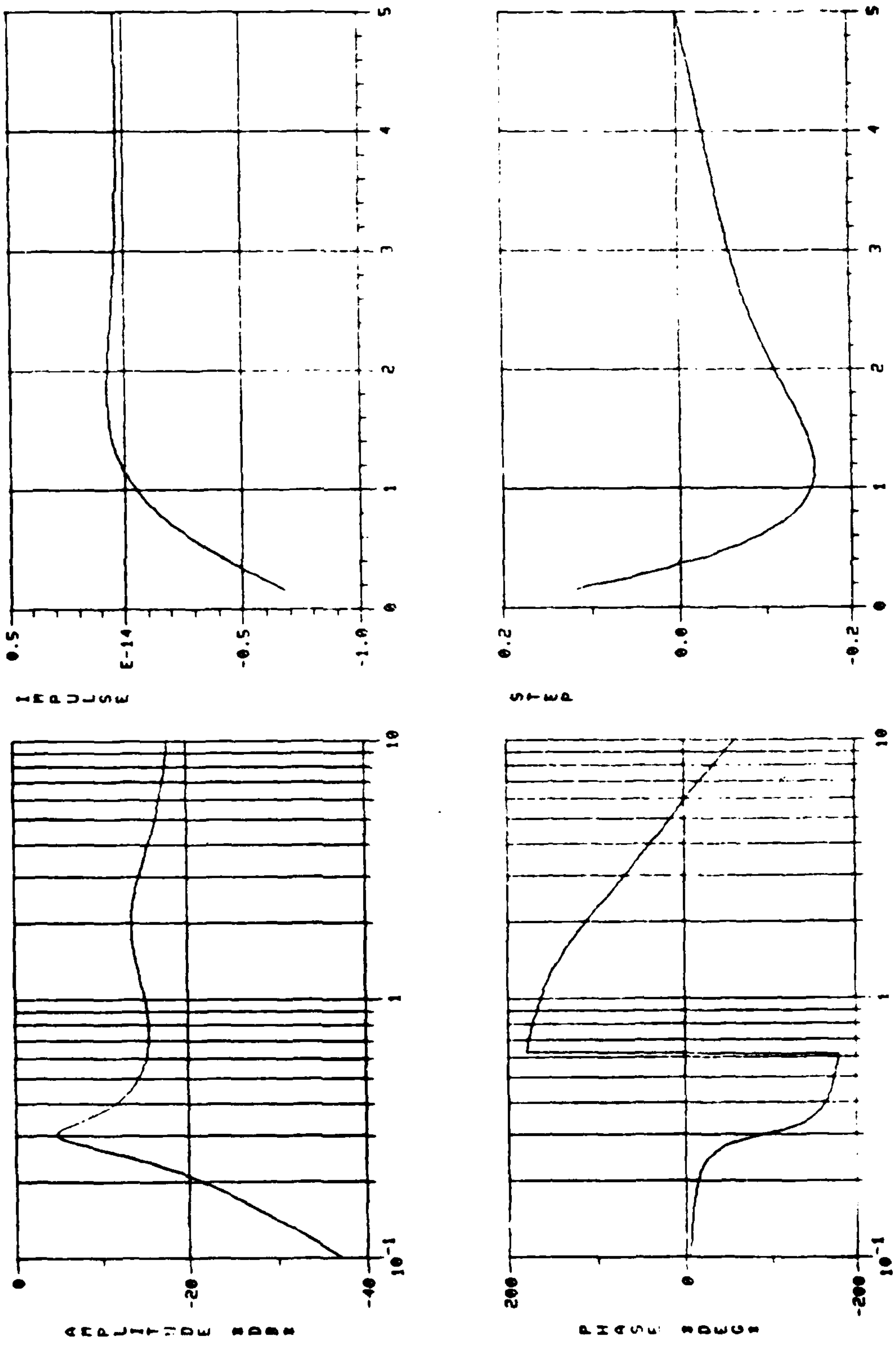

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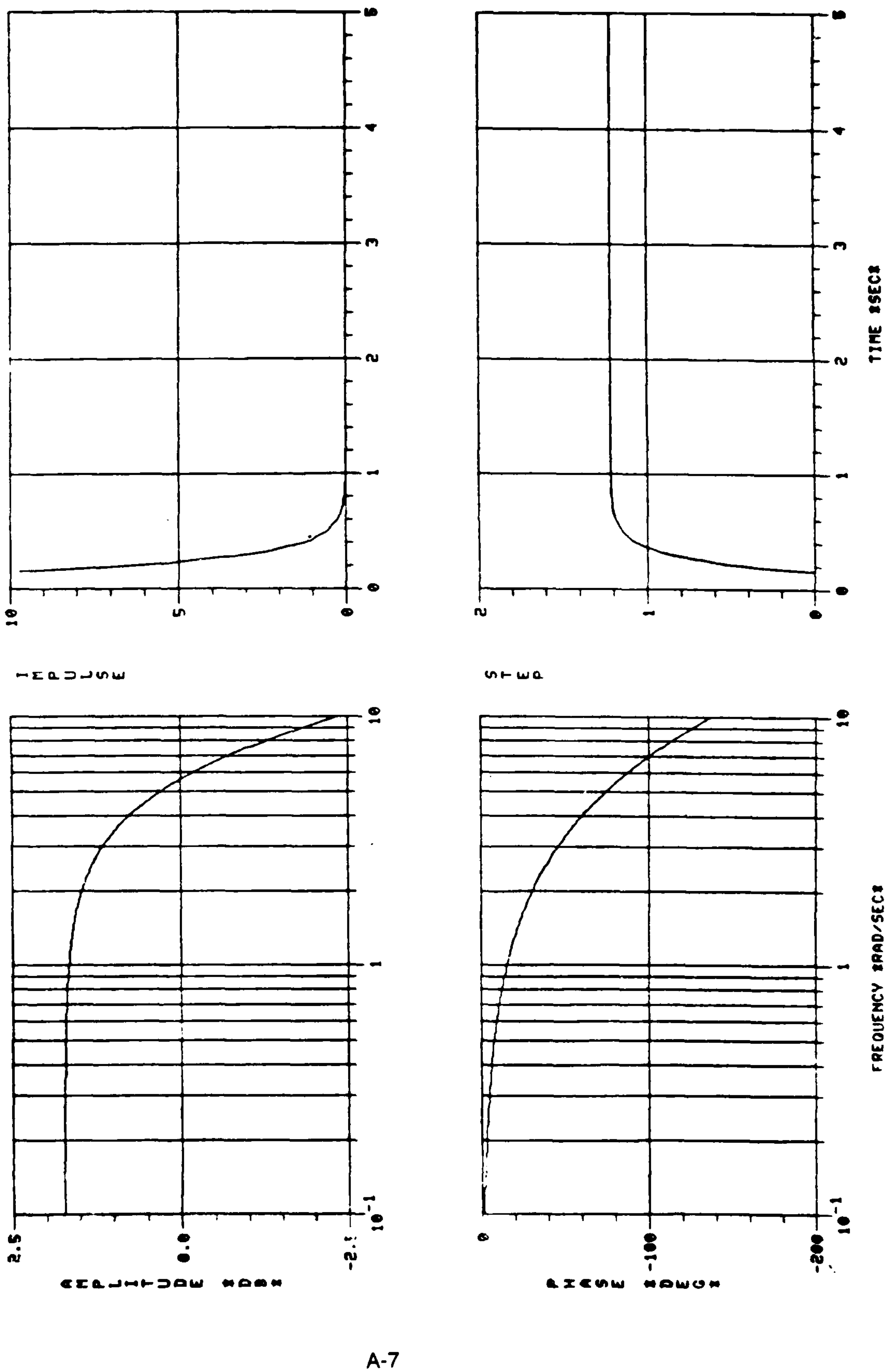

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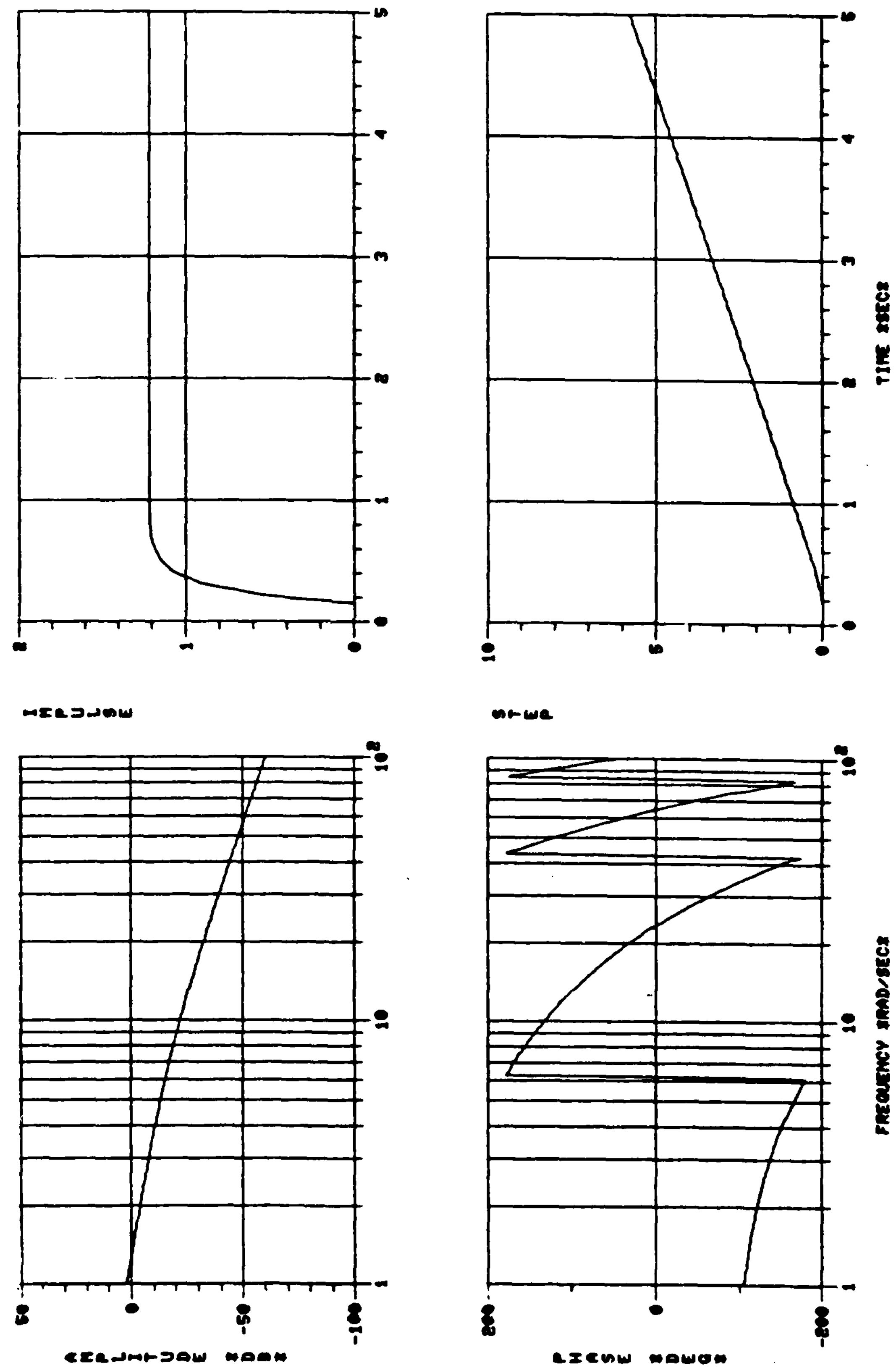

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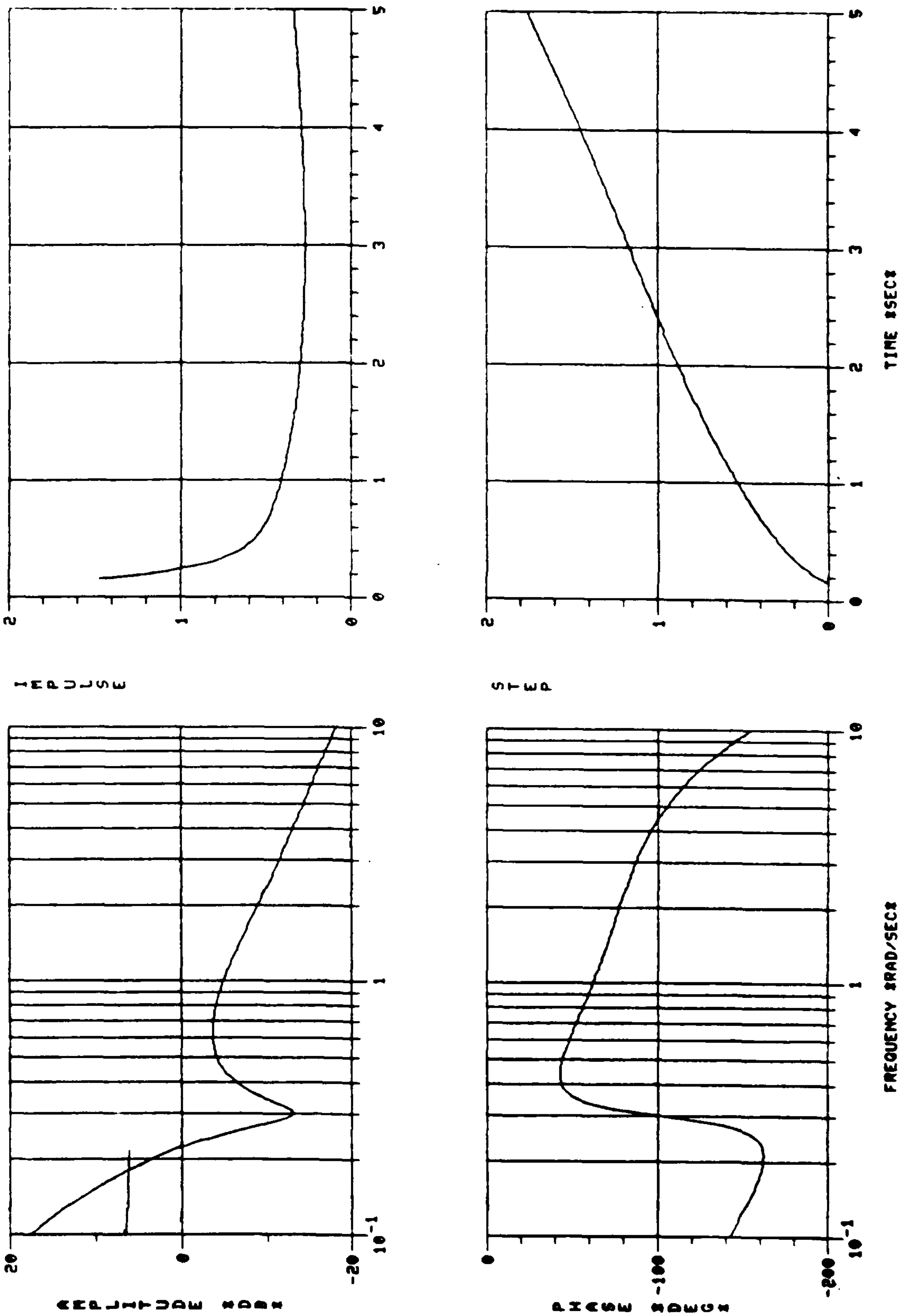
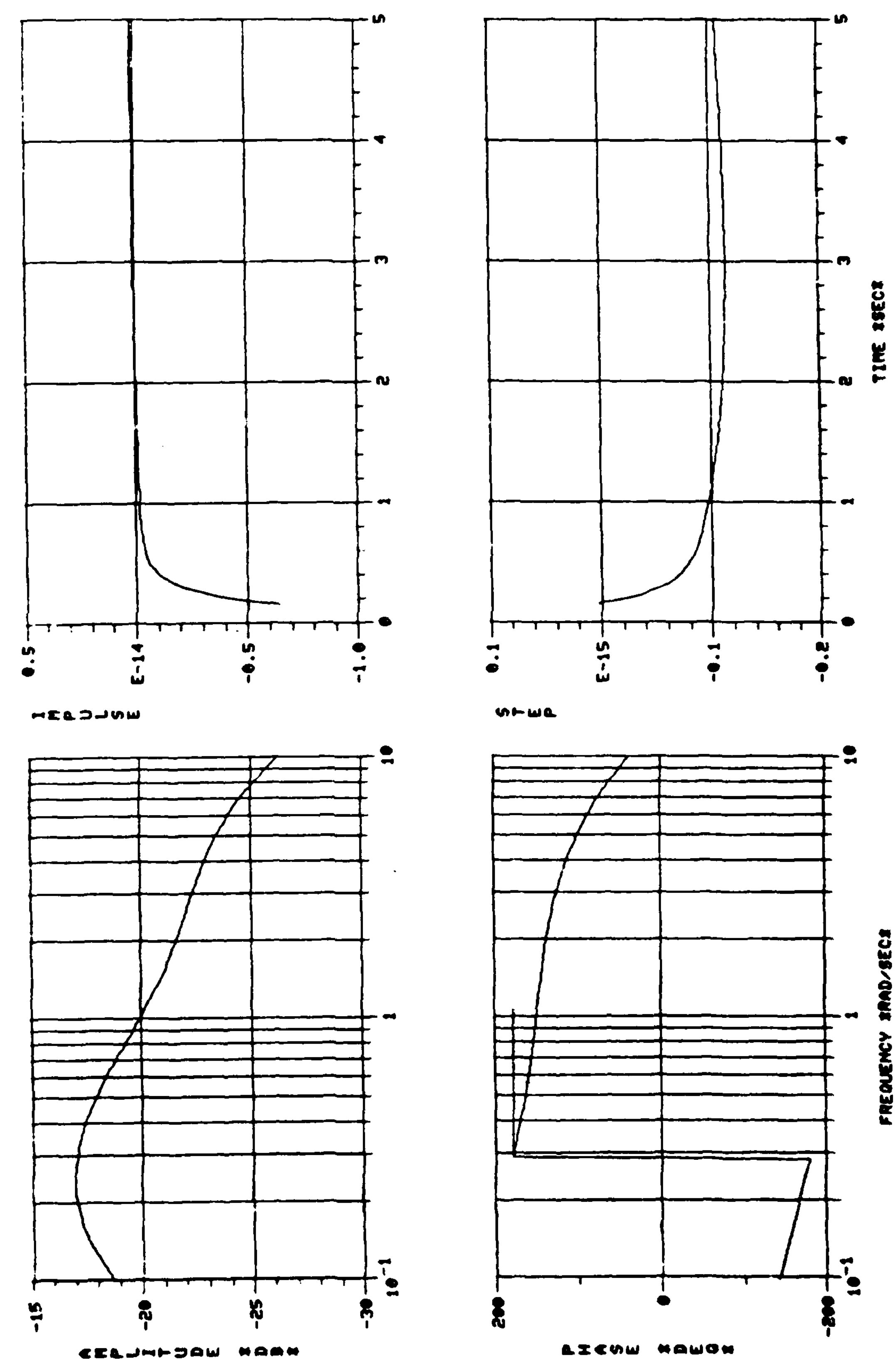
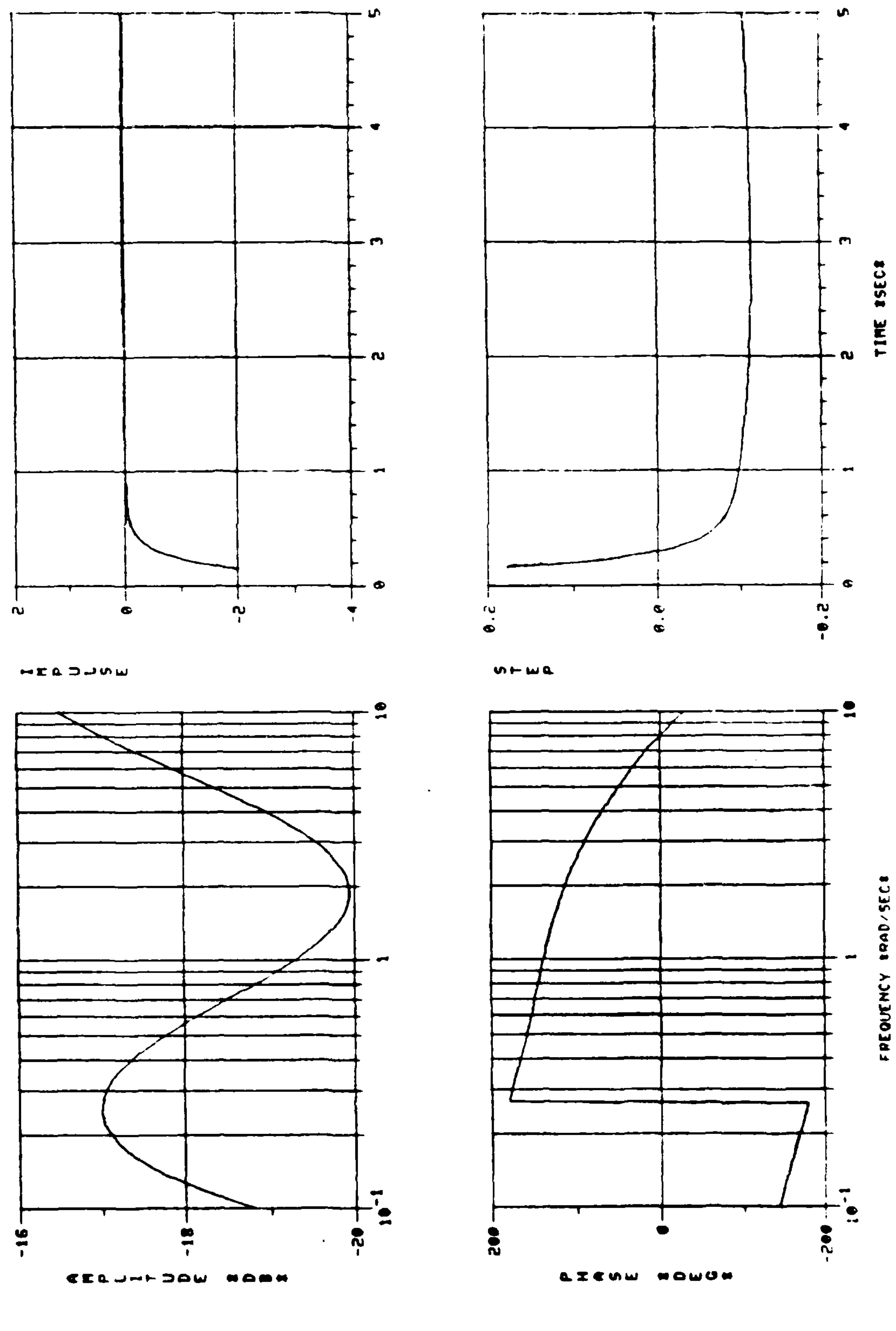
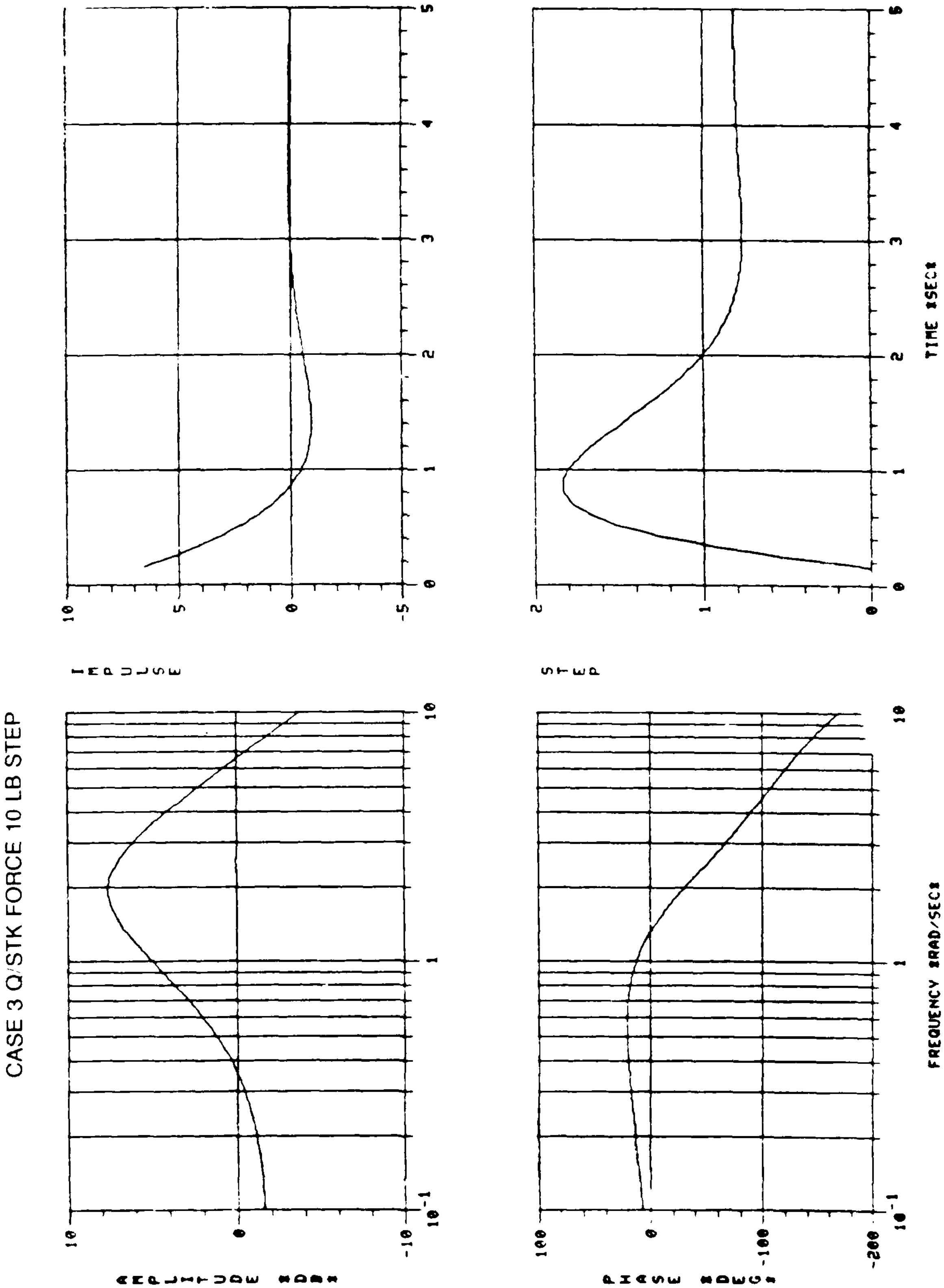




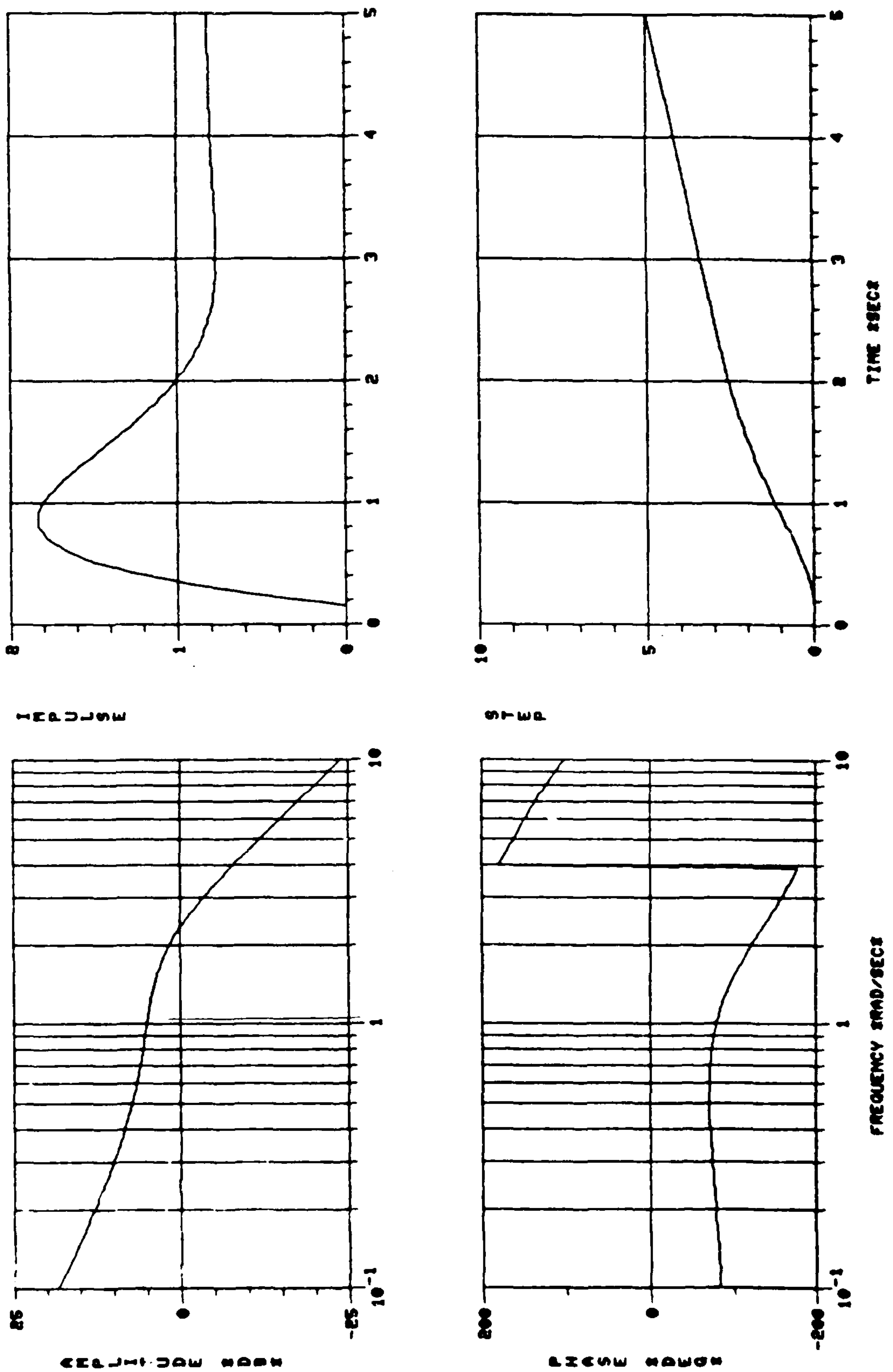
CASE 2 NZP/STK FORCE 10 LB STEP

CASE 2 NZCG/STK FORCE 10 LB STEP




CASE 3 Q/STK FORCE 10 LB STEP
IMPULSE
STEP
TIME
FREQUENCY
AMPLITUDE
PHASE

CASE 3 THETA/STK FORCE 10 LB STEP



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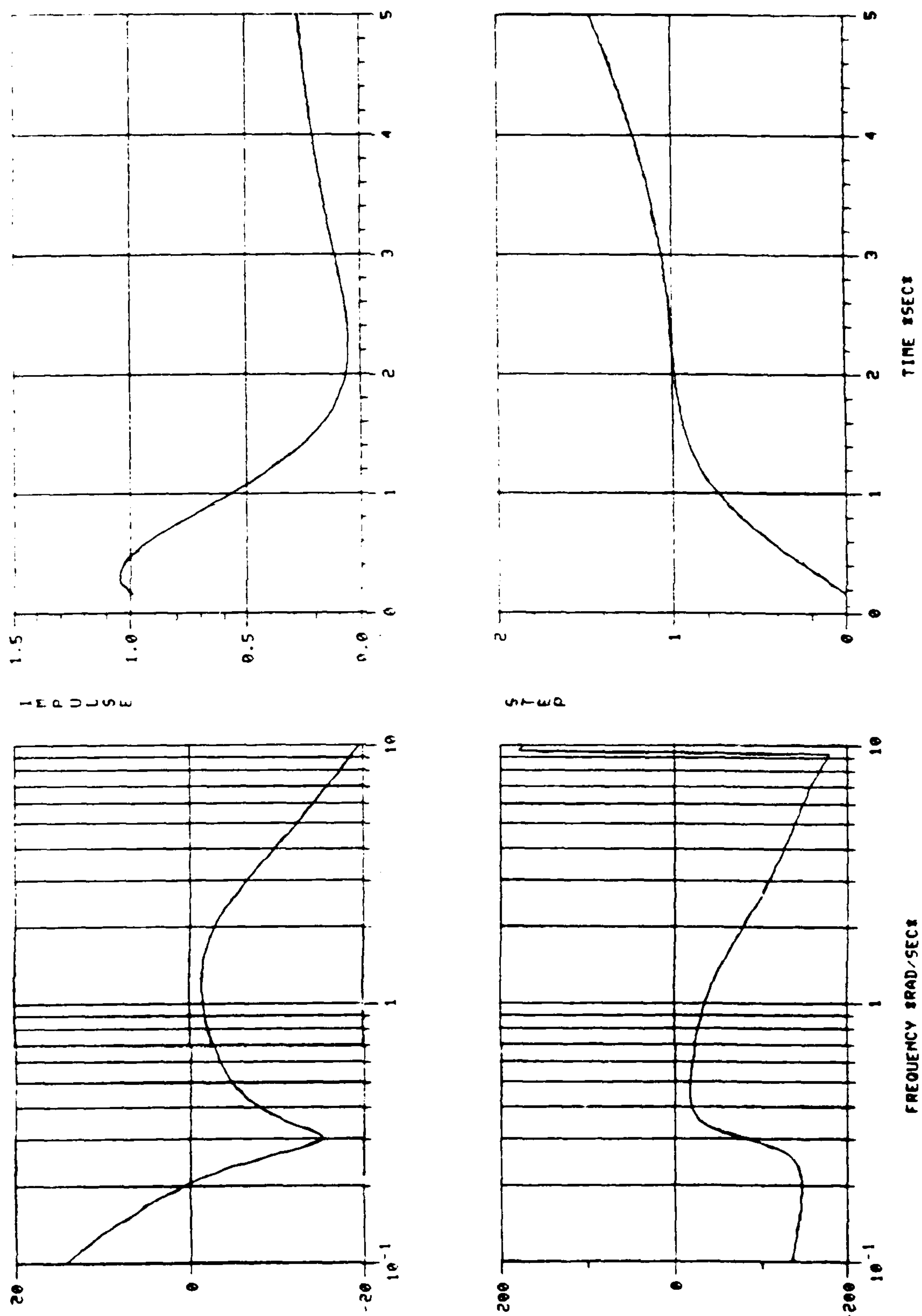
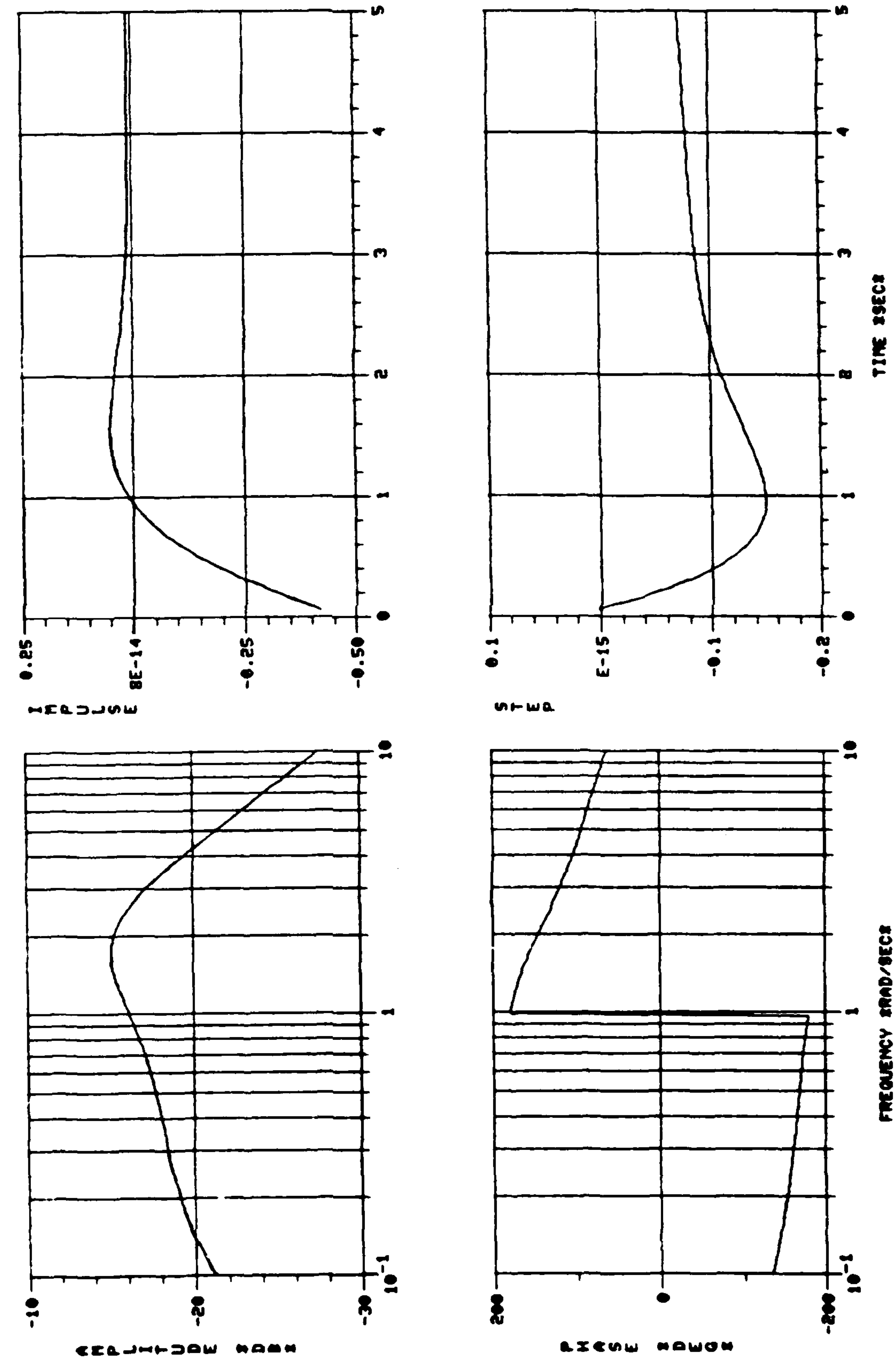


CASE 3 NZP/STK FORCE 10 LB STEP



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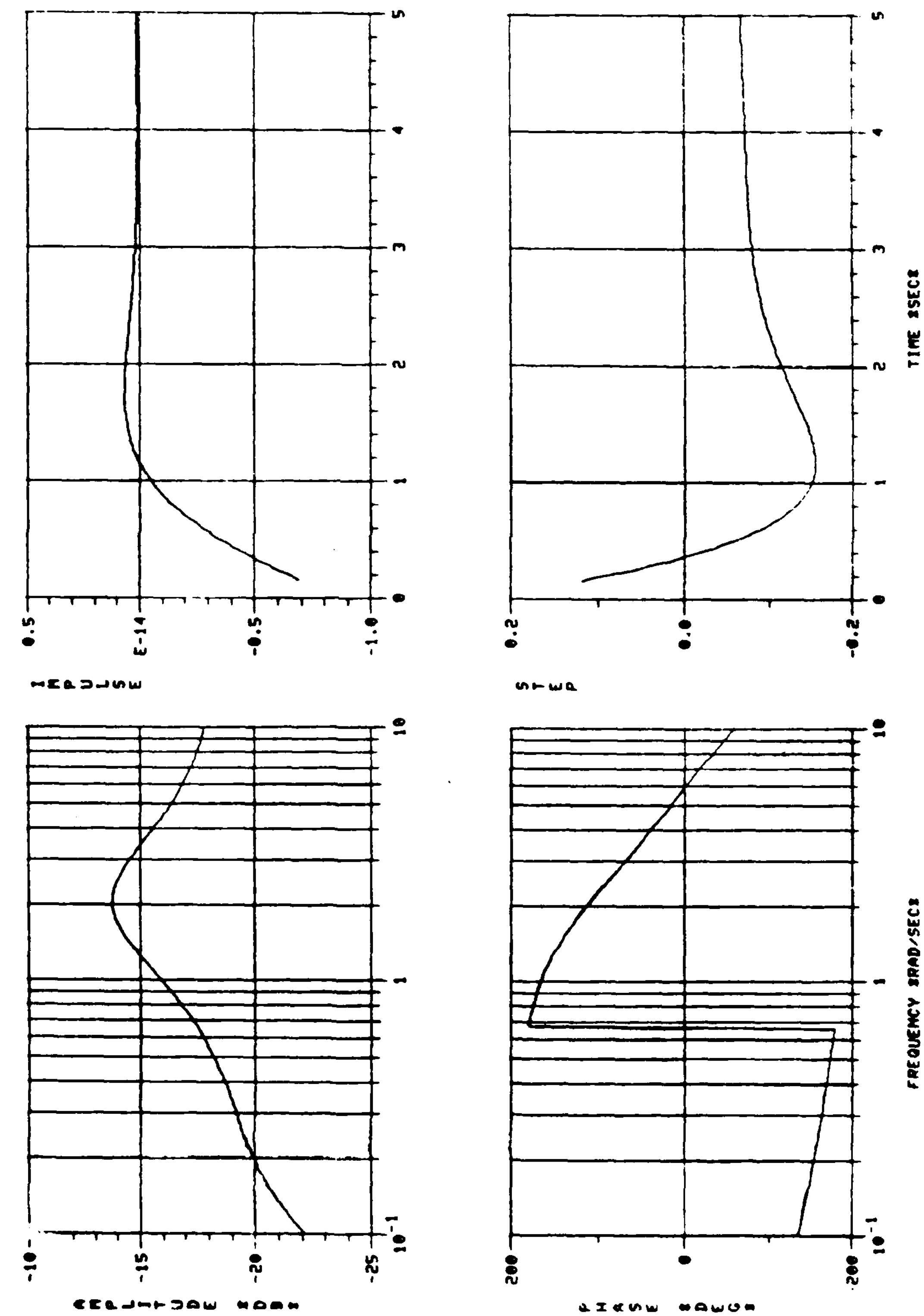

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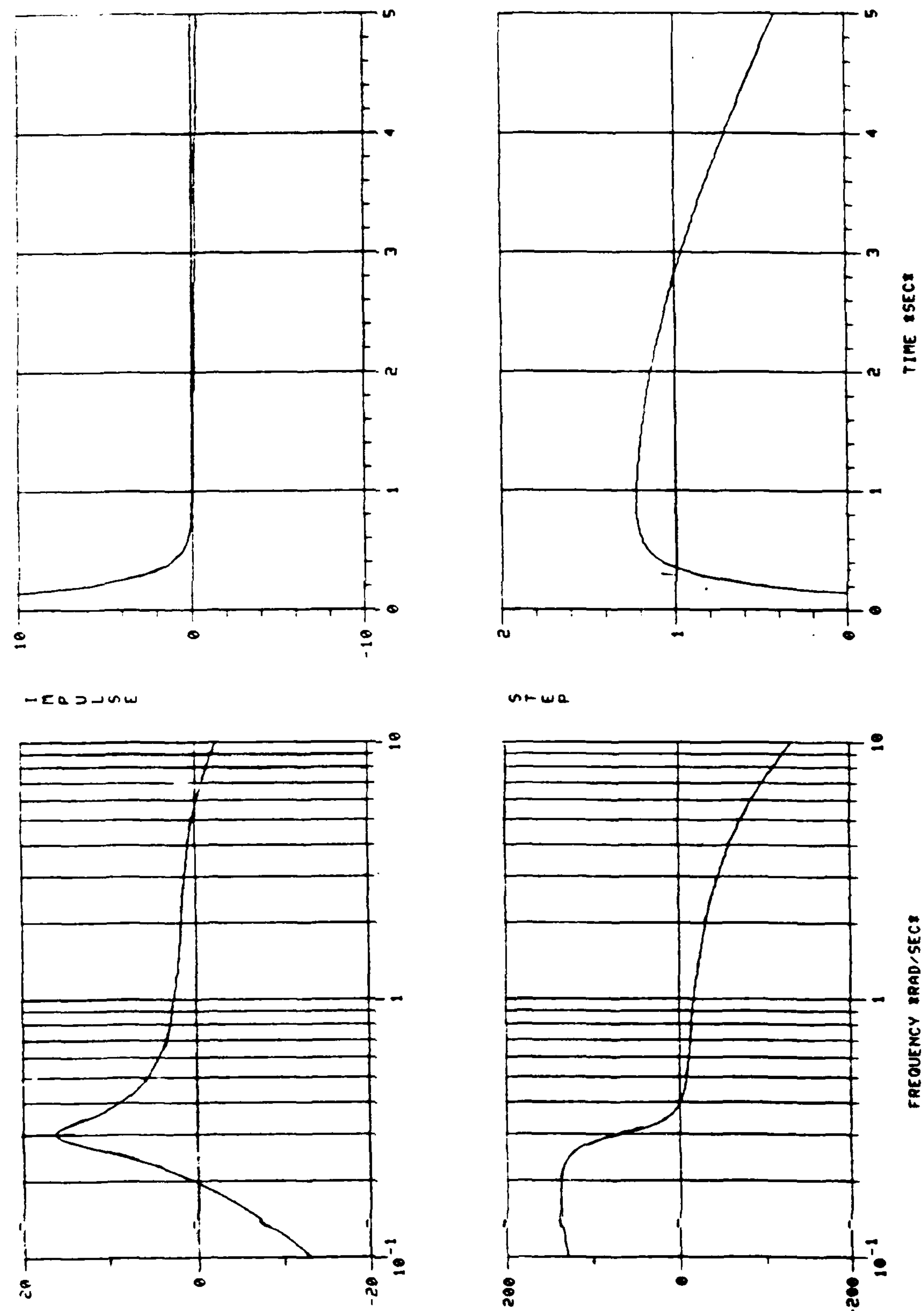

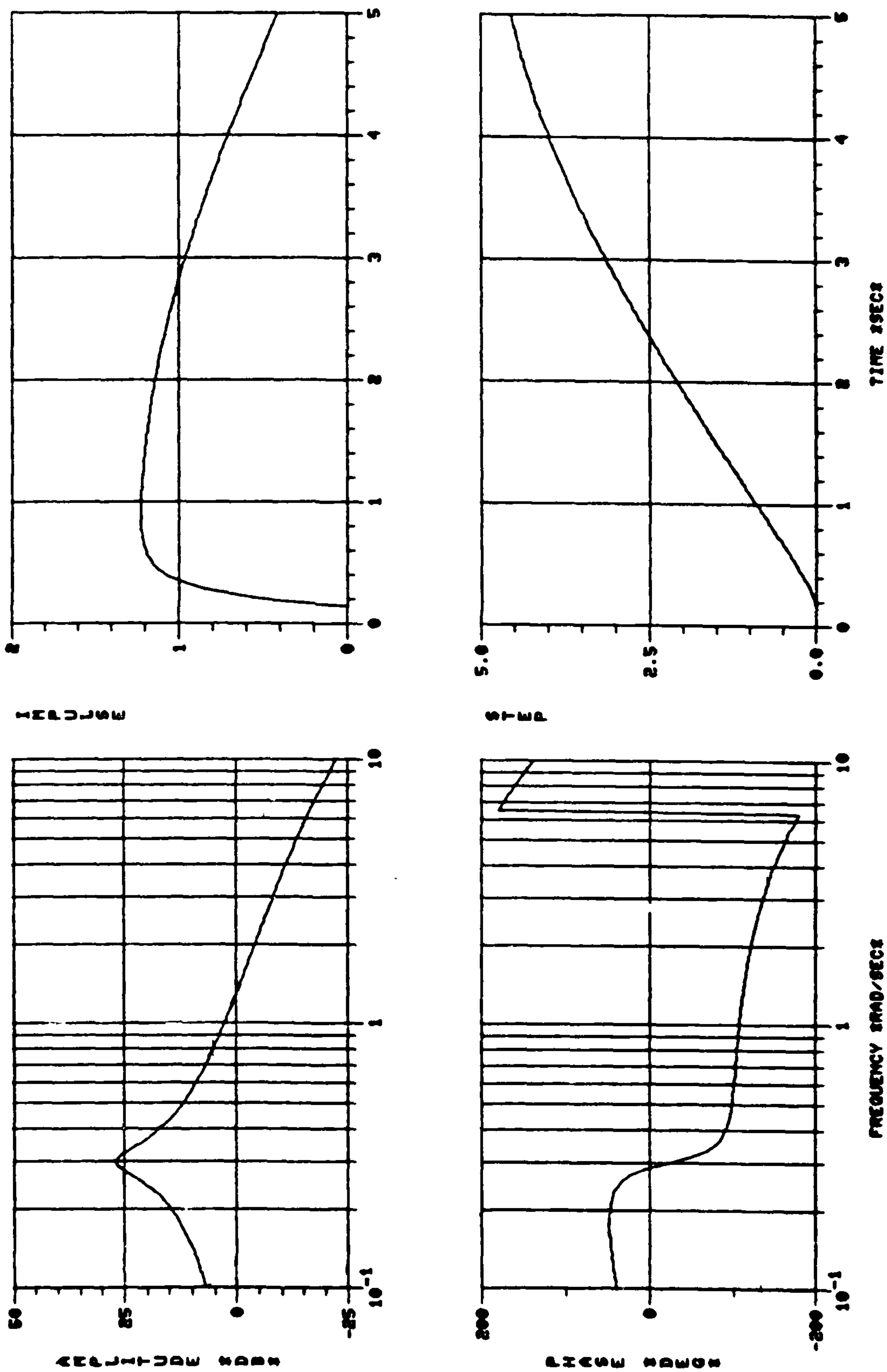

CASE 4 THETA/STK FORCE 10 LB STEP

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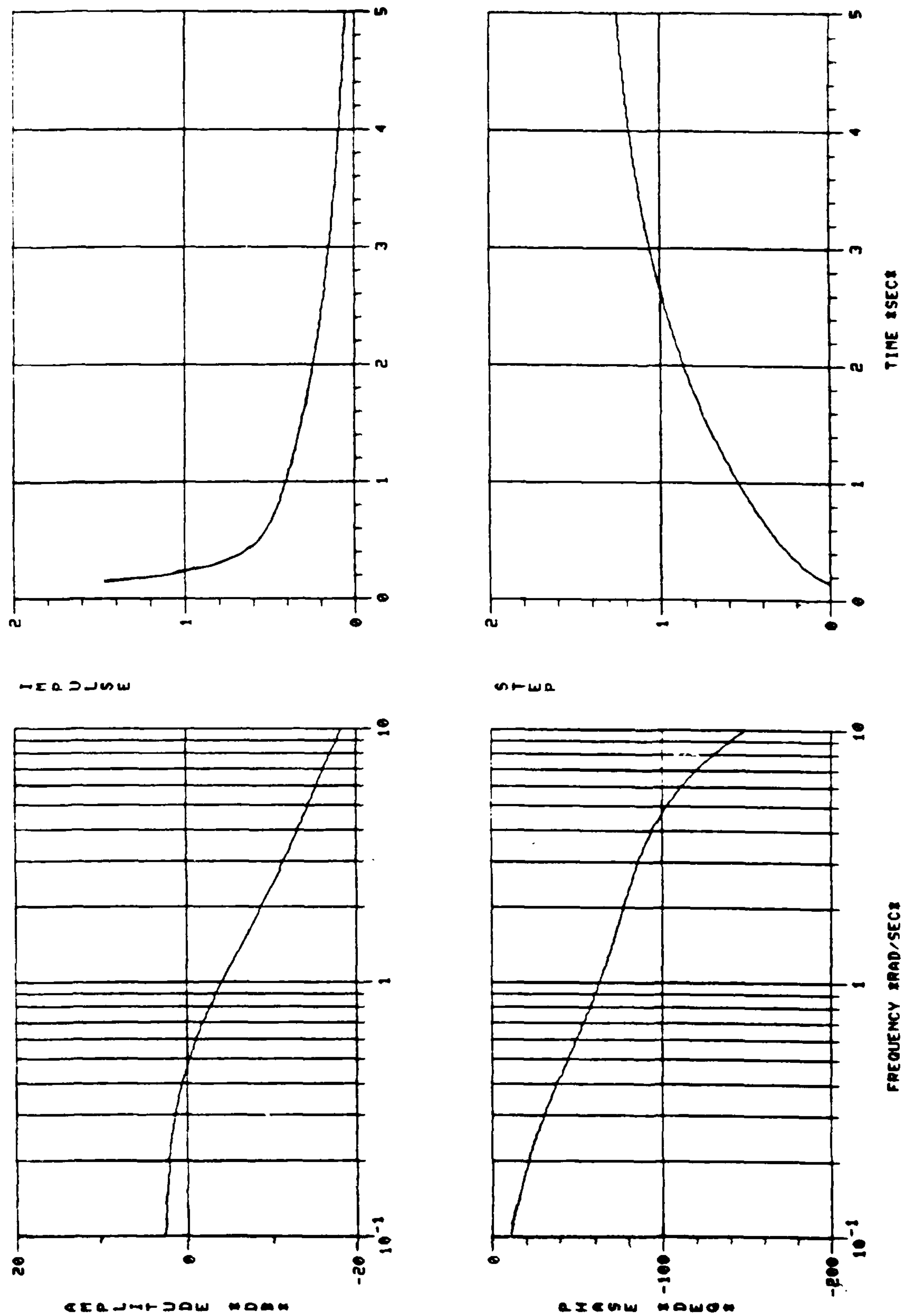
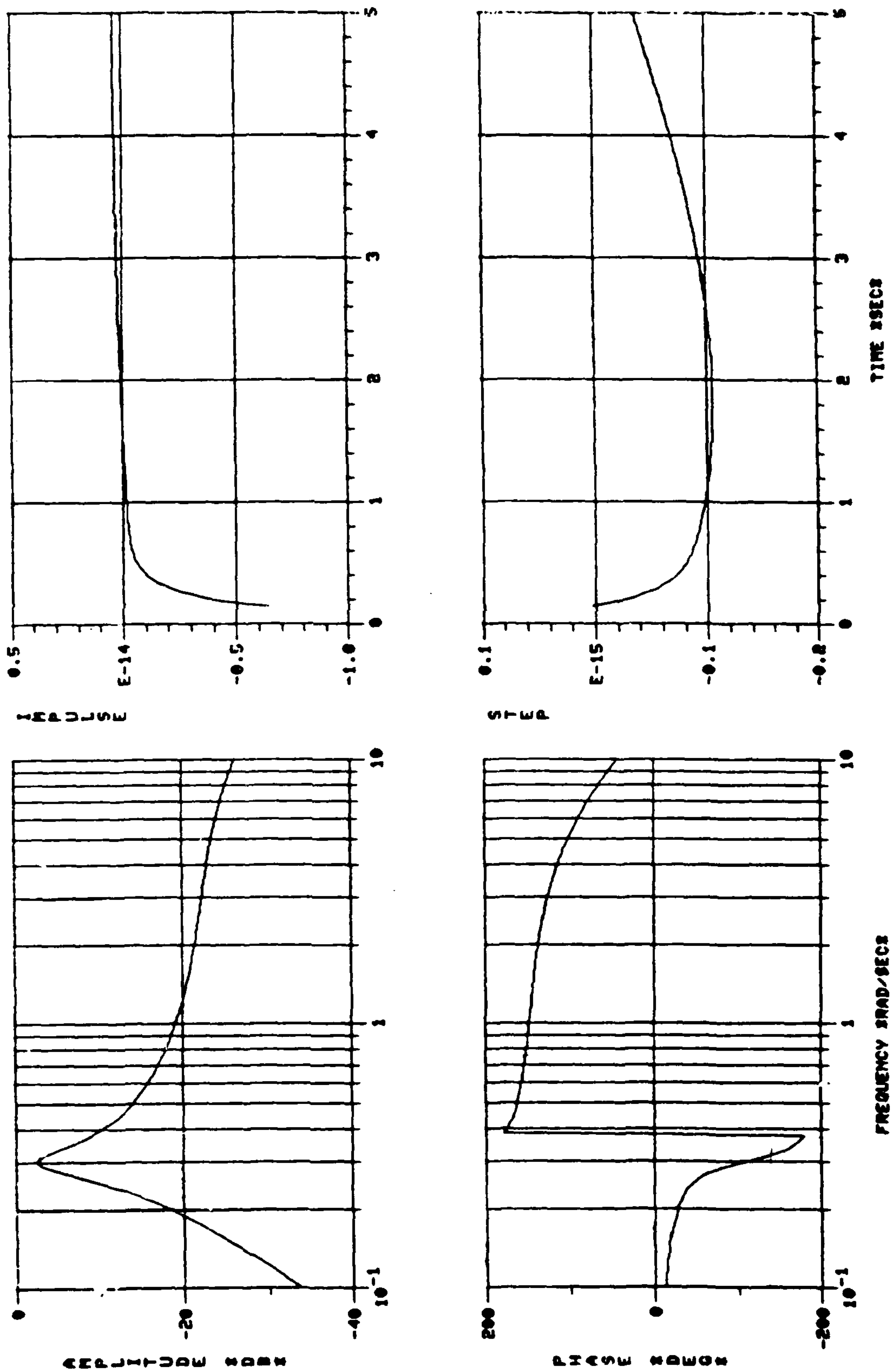
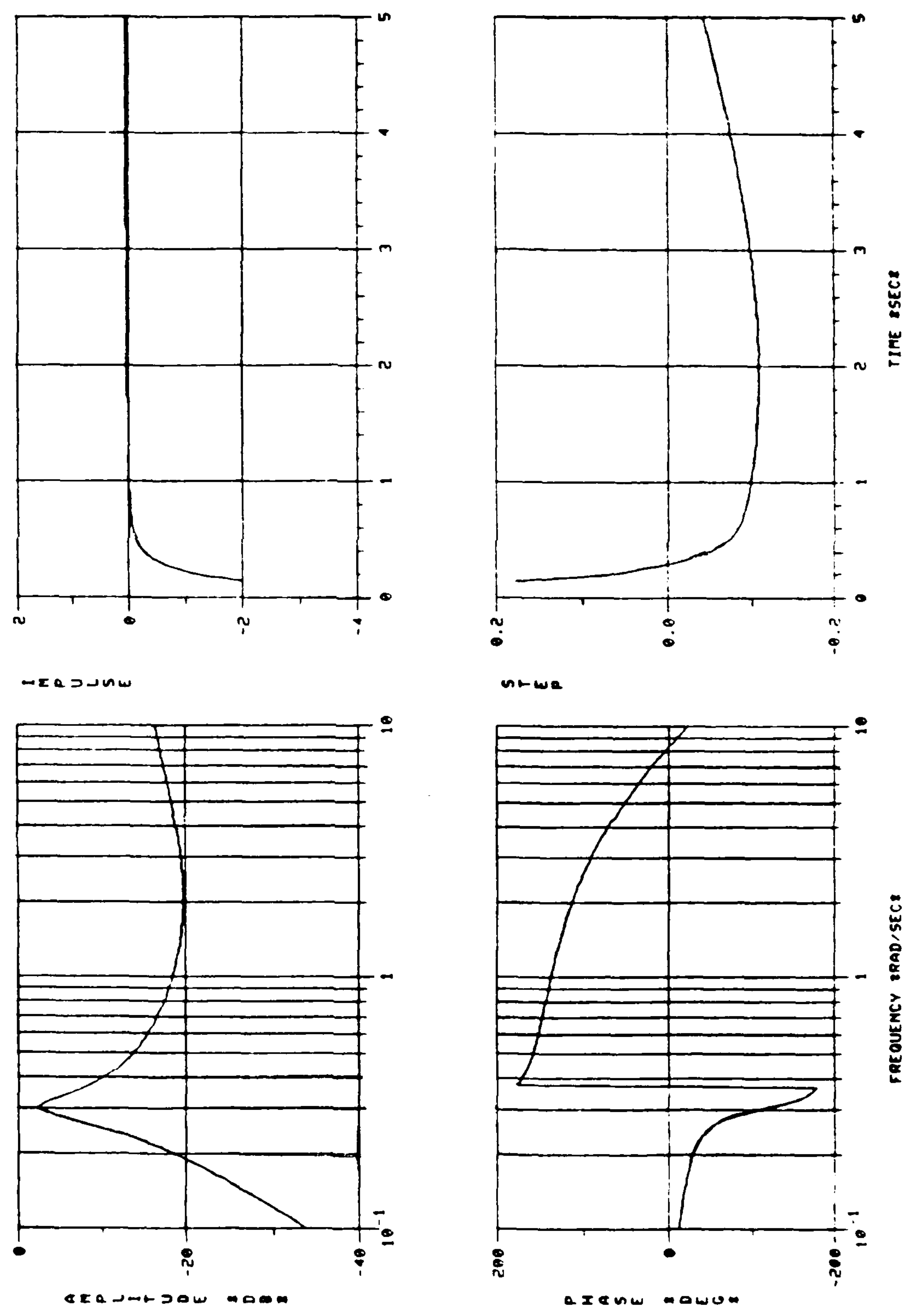


CASE 4 NZP/STK FORCE 10 LB STEP



CASE 4 NZCG/STK FORCE 10 LB STEP



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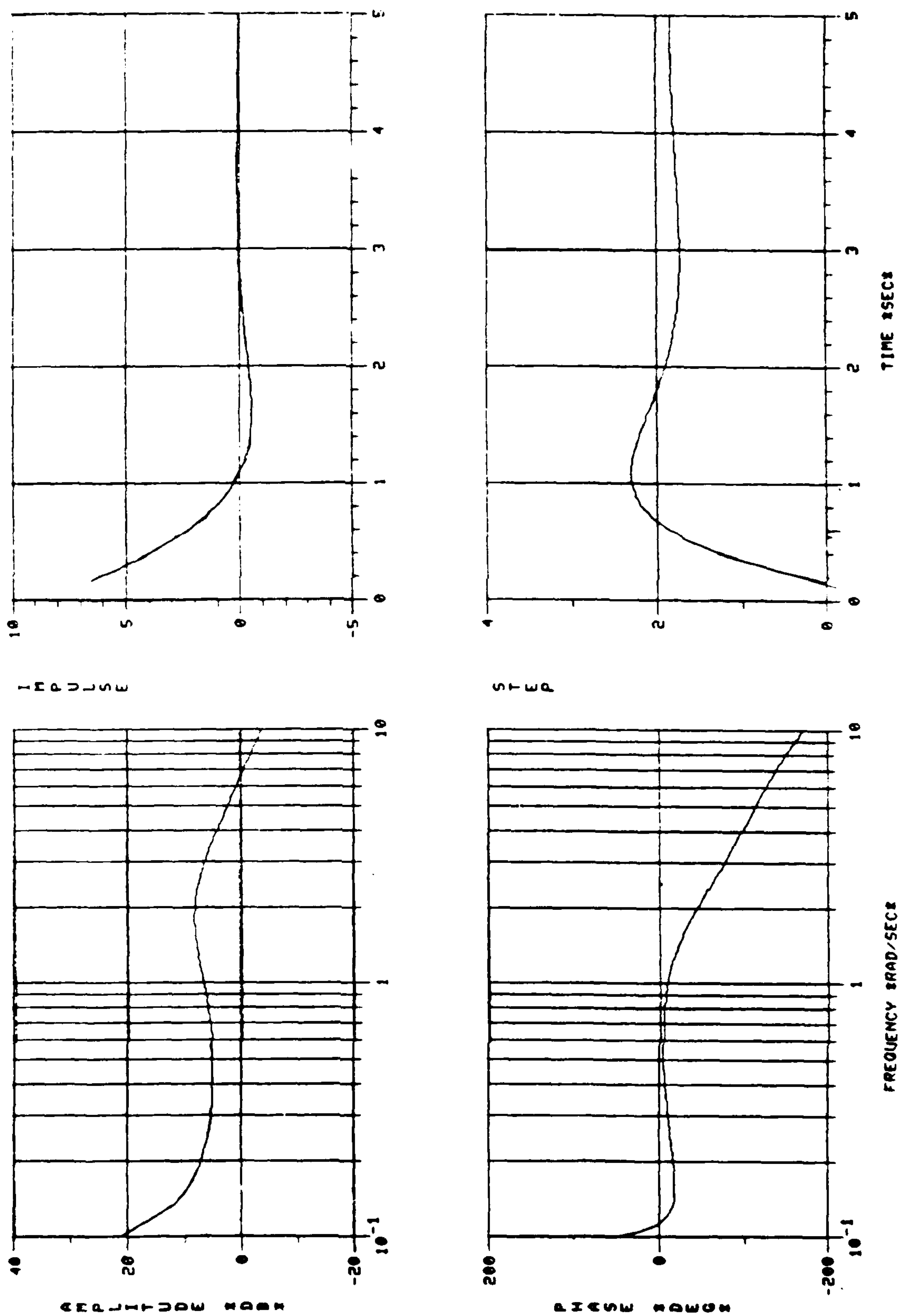
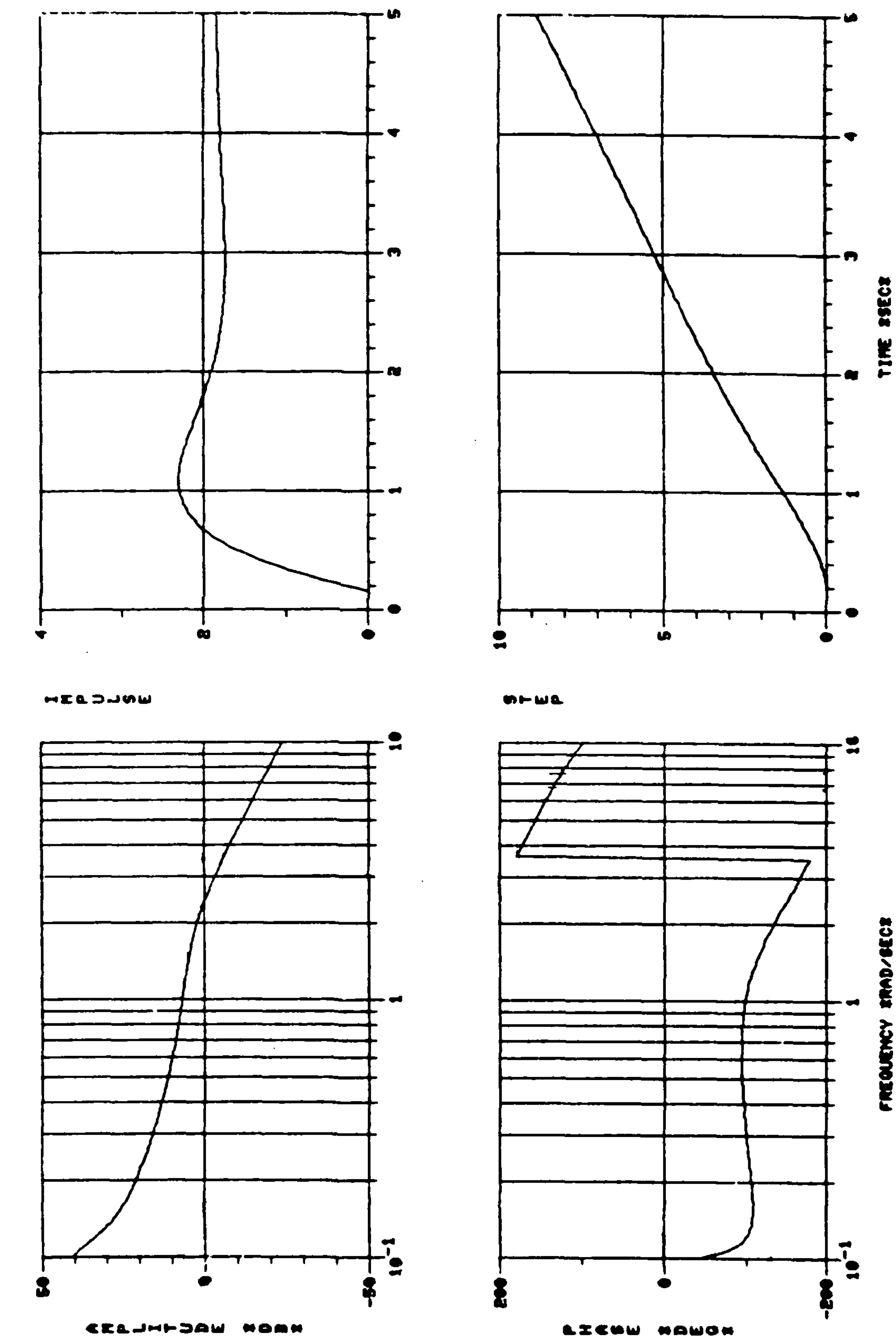
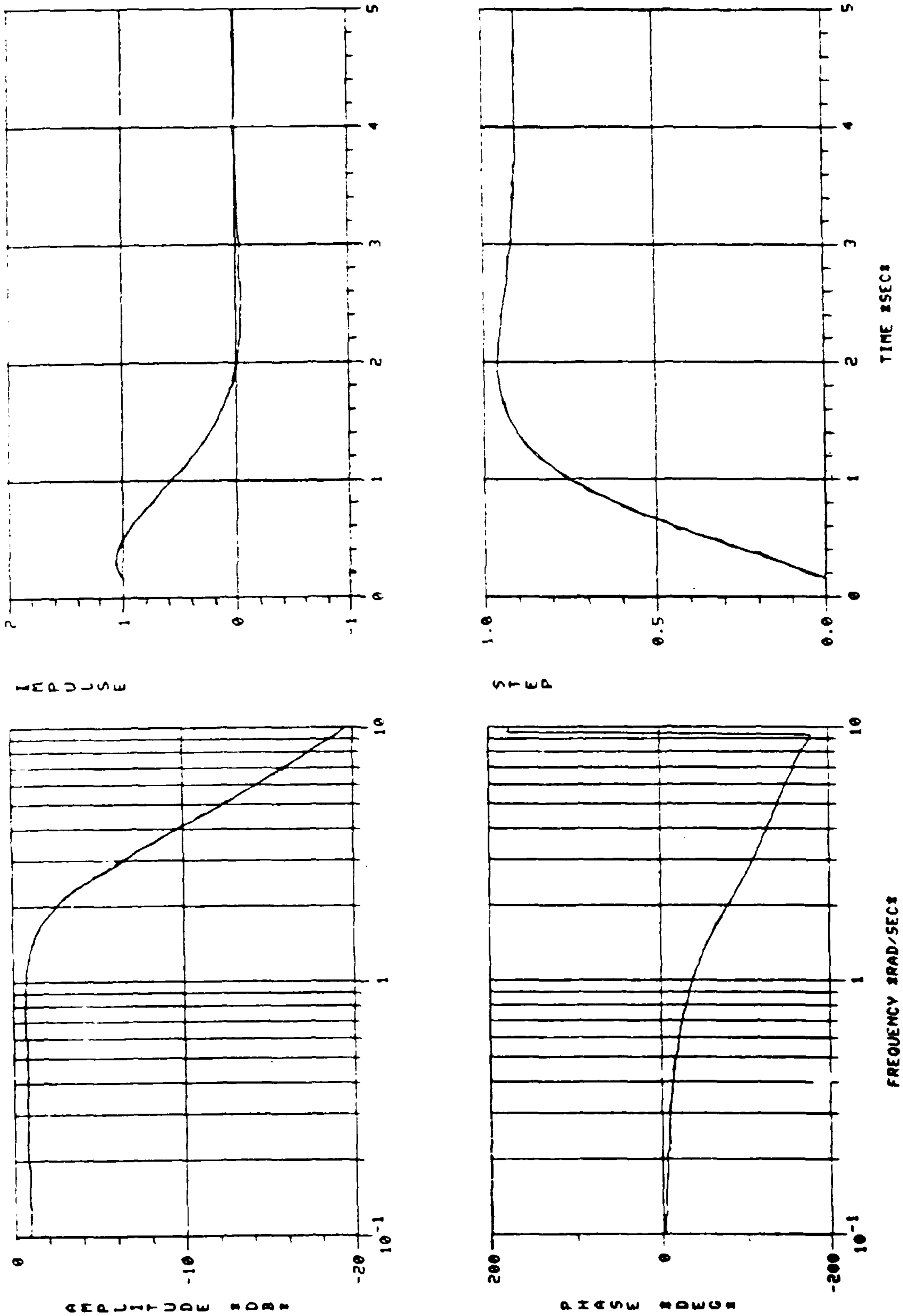




CASE 5 THETA/STK FORCE 10 LB STEP

CASE 5 ALFA/STK FORCE 10 LB STEP



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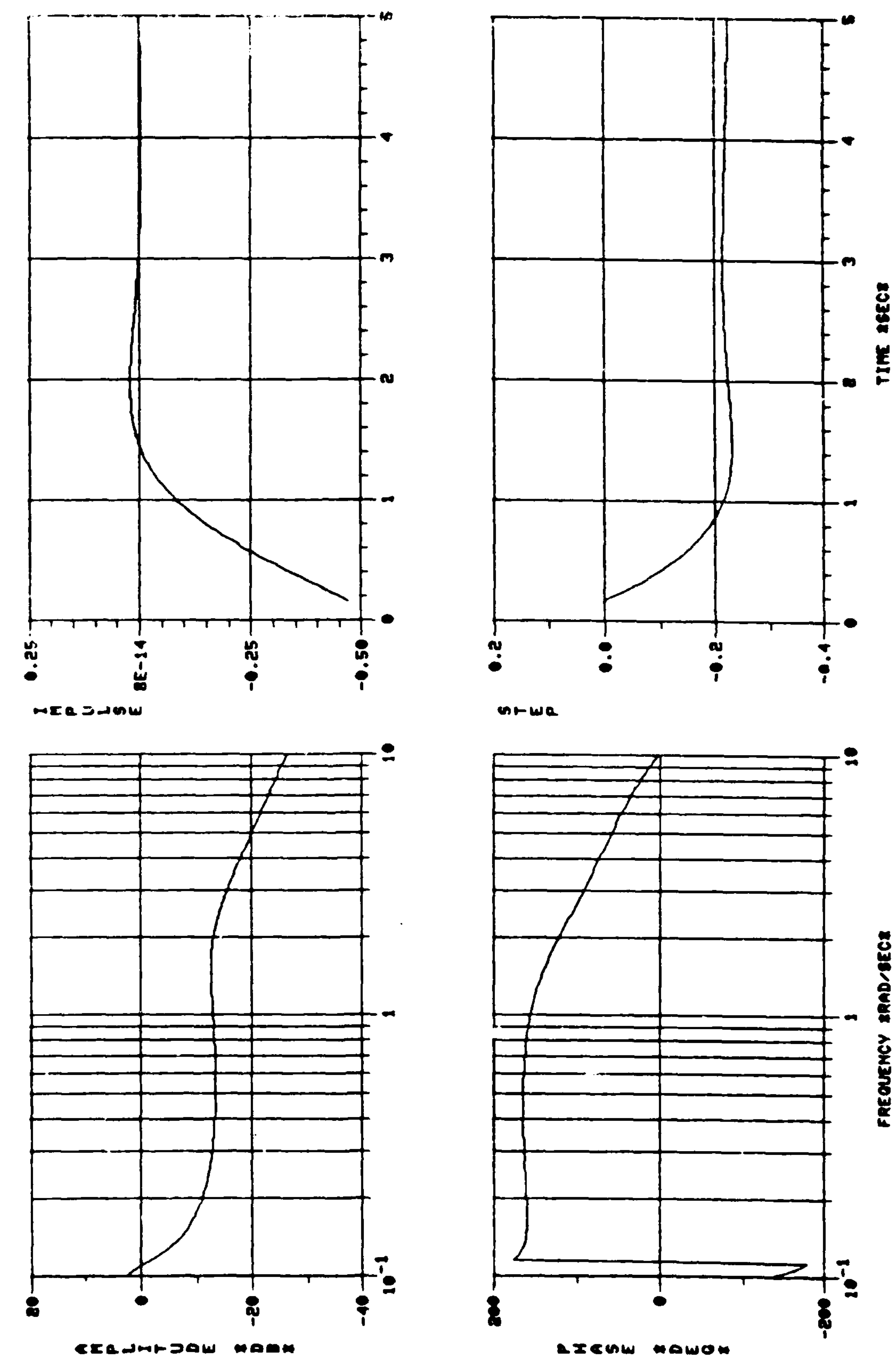

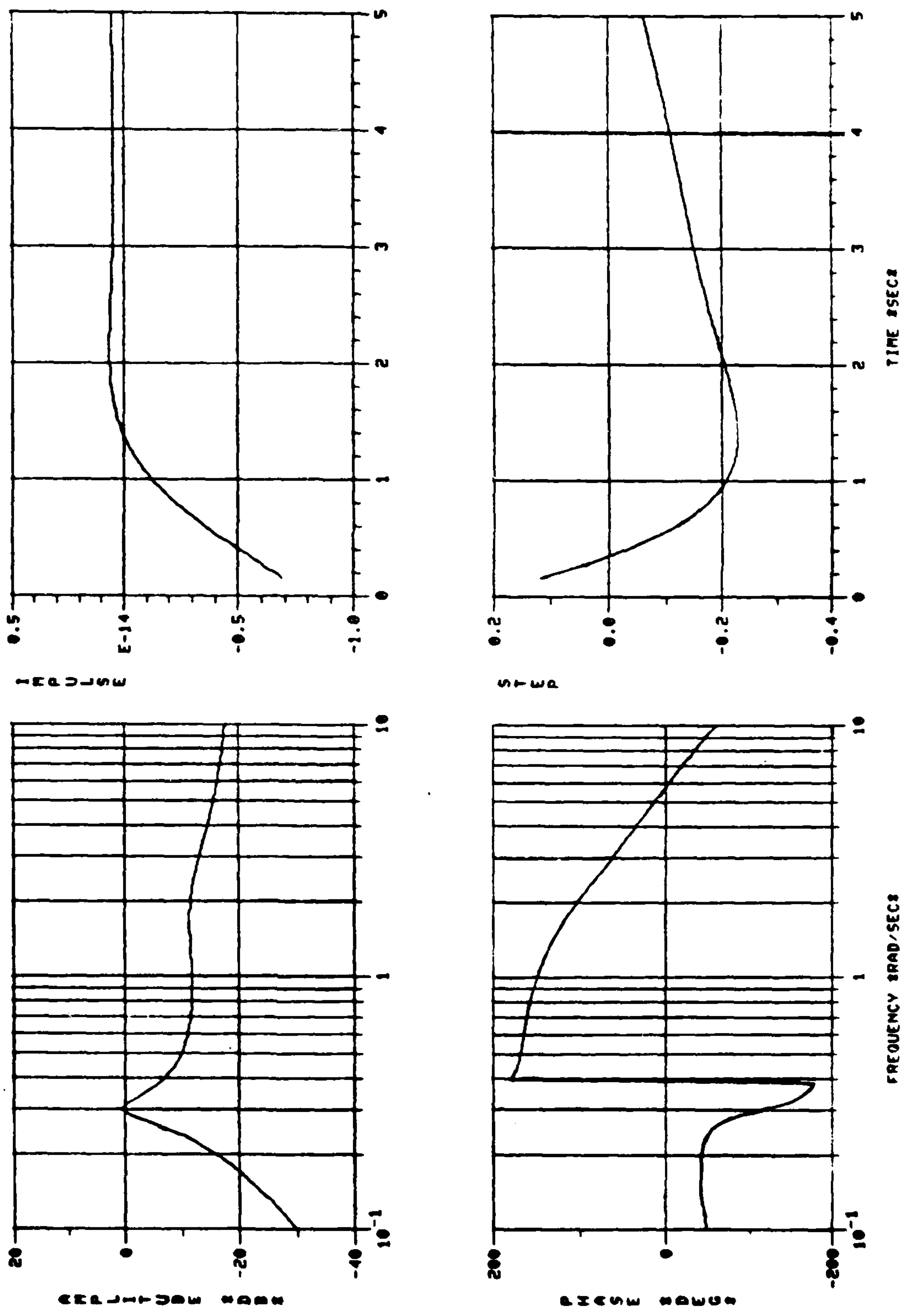

CASE 5 NZCG/STK FORCE 10 LB STEP

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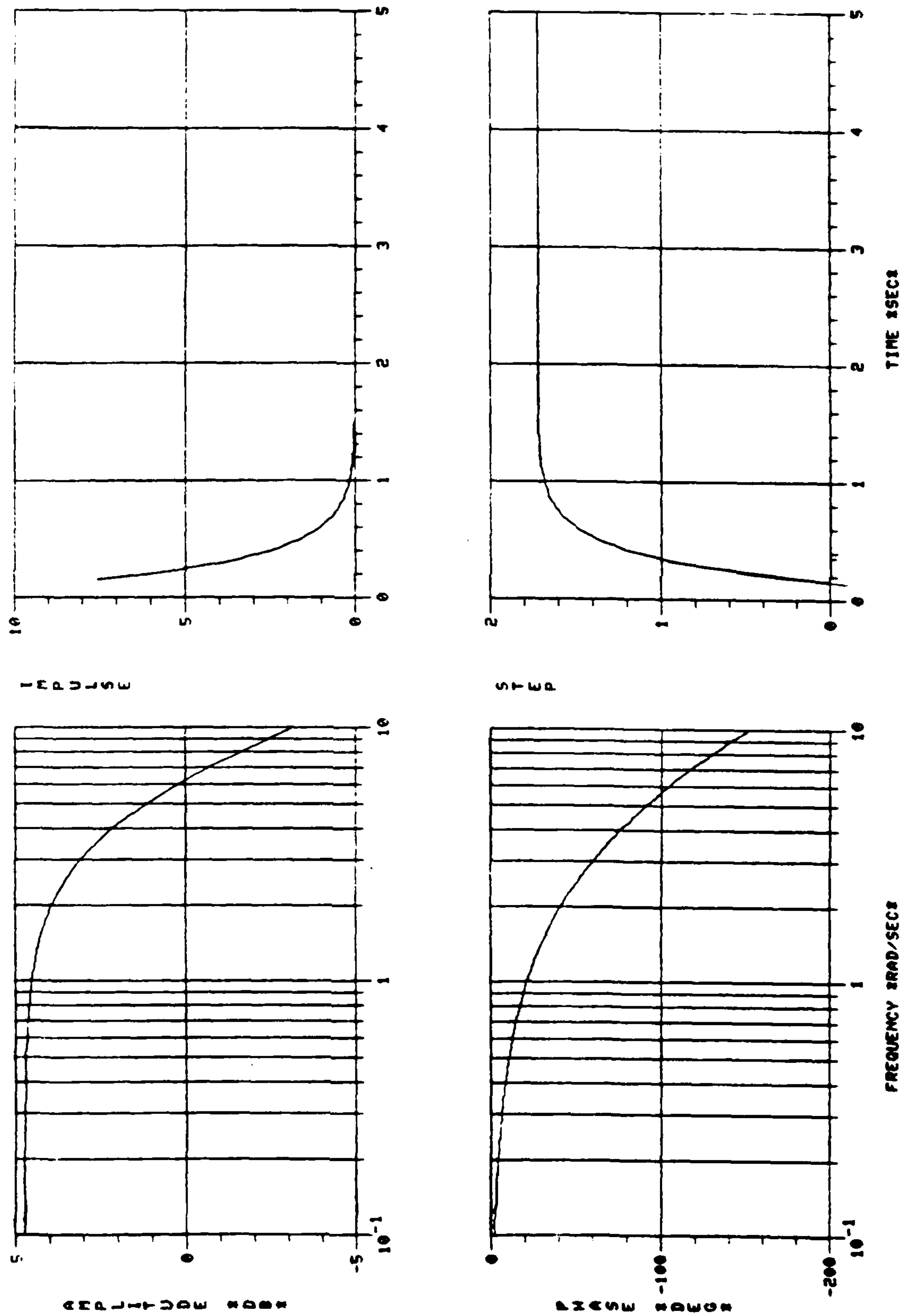

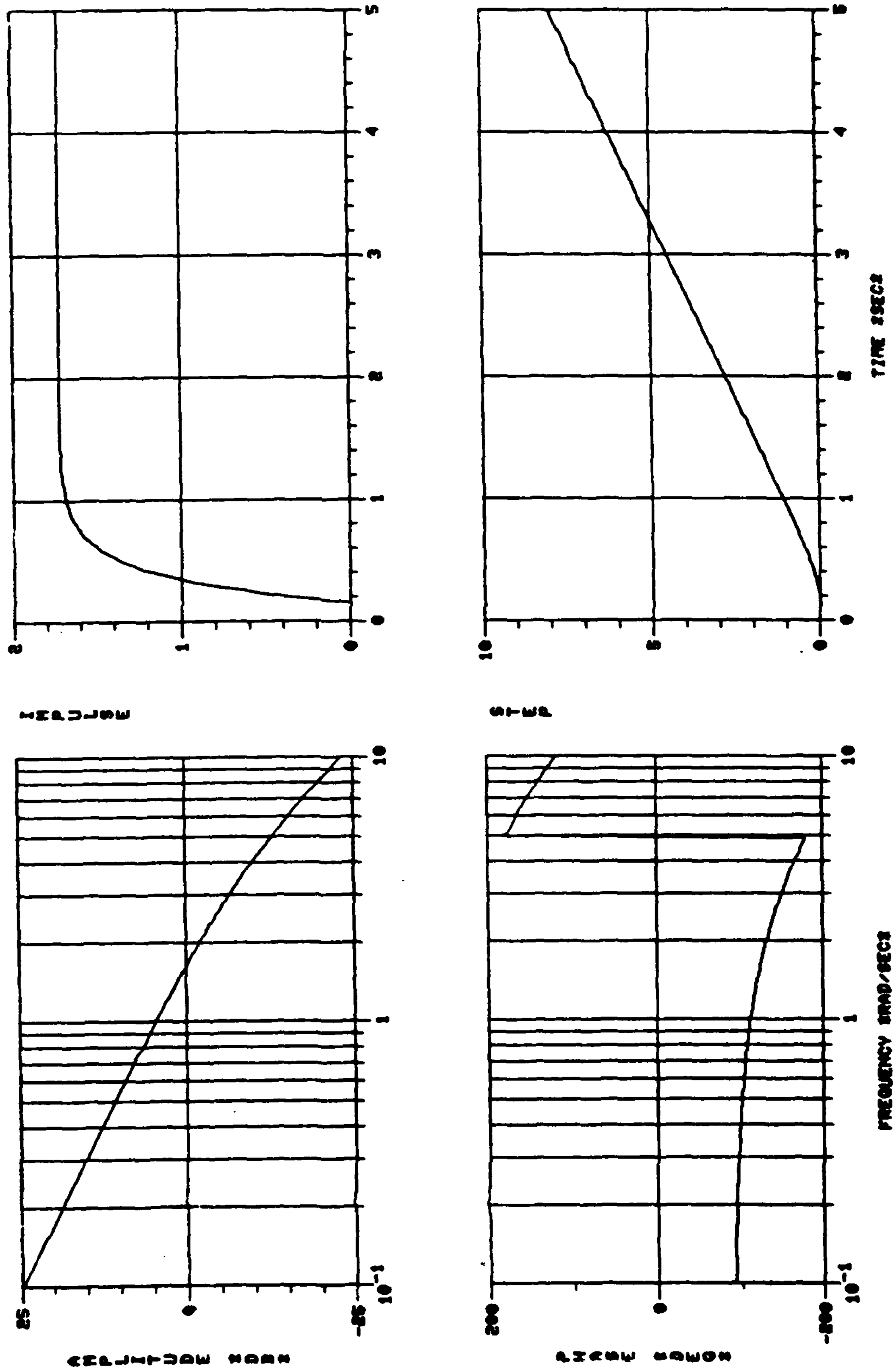

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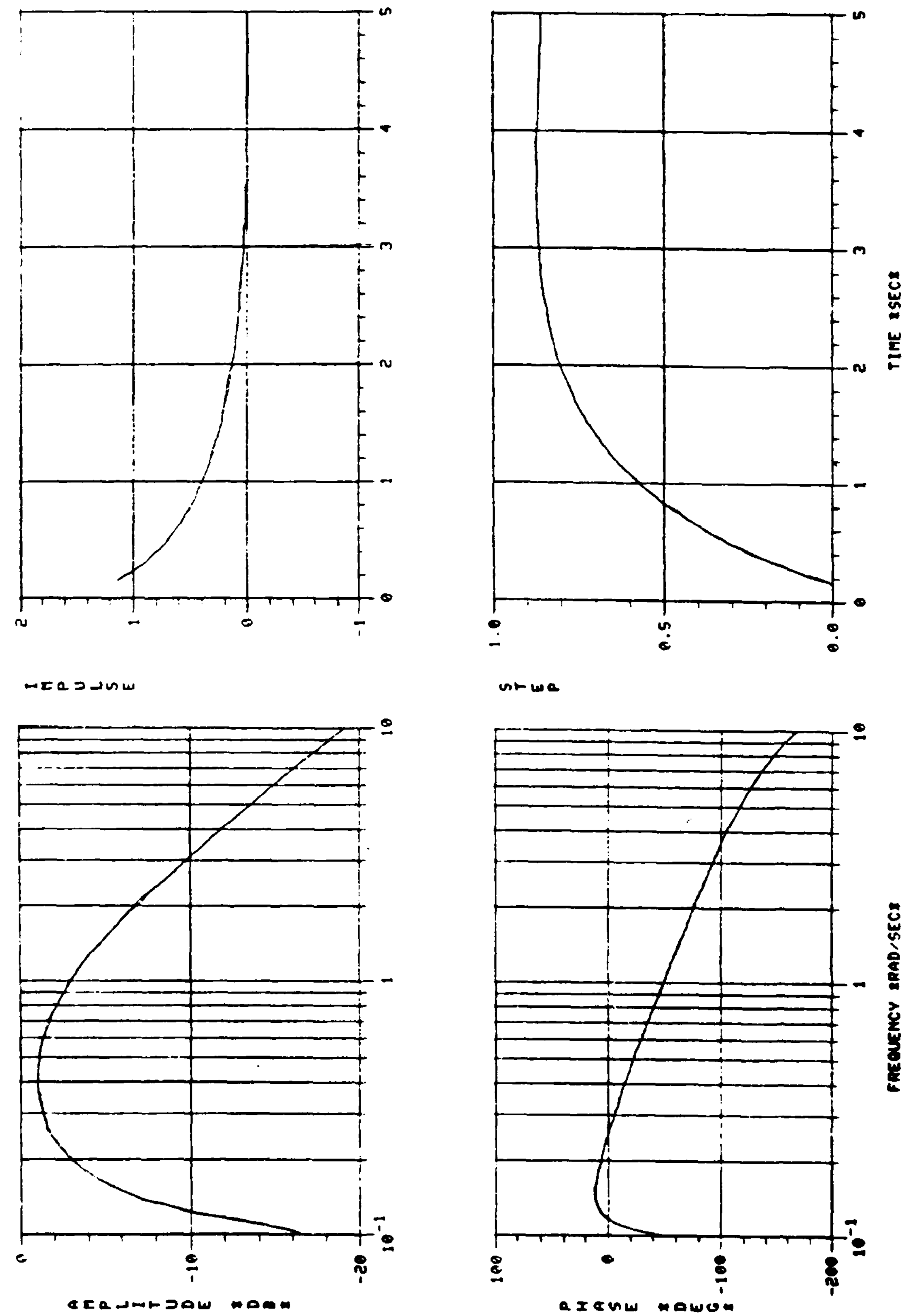
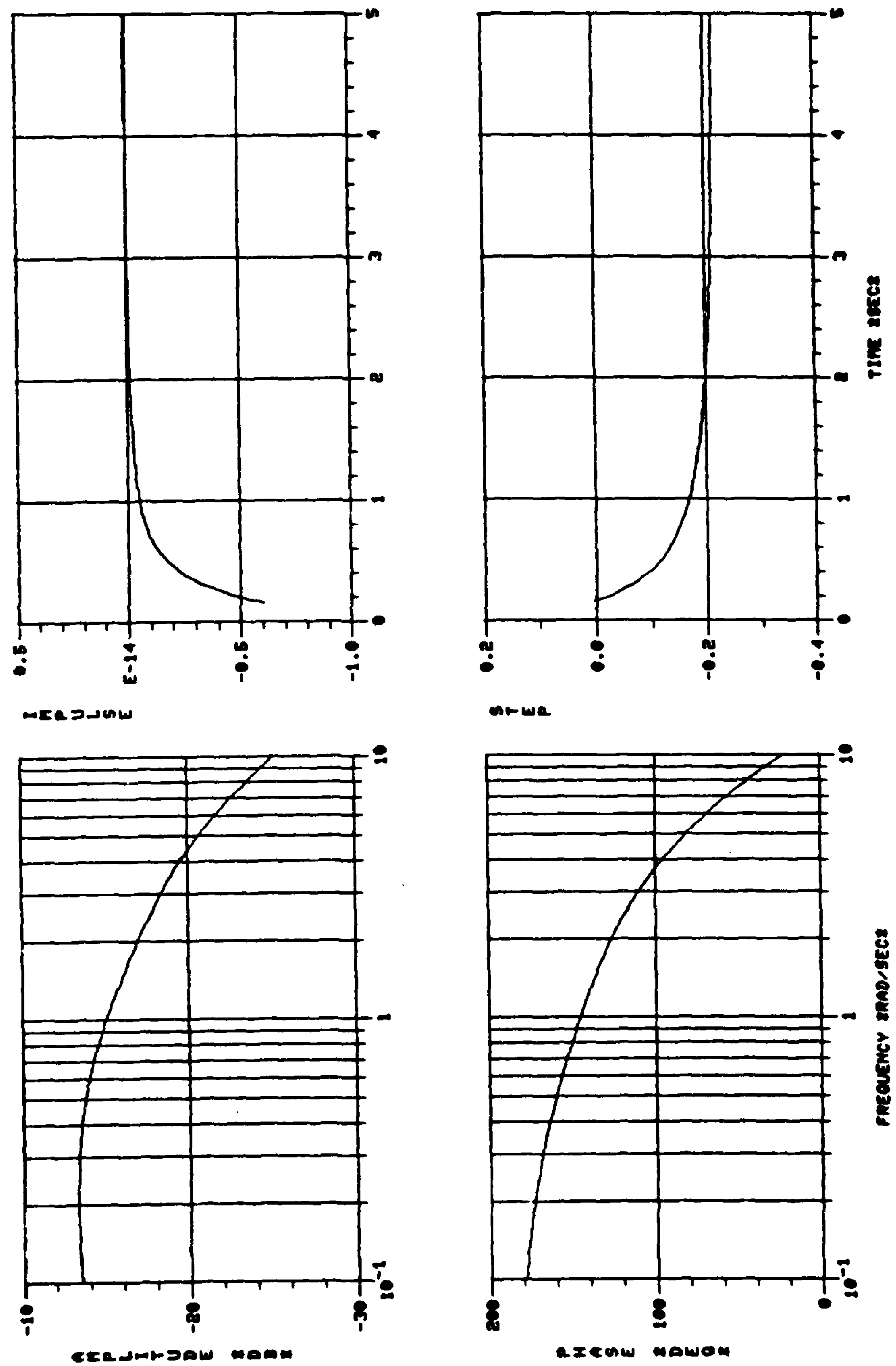
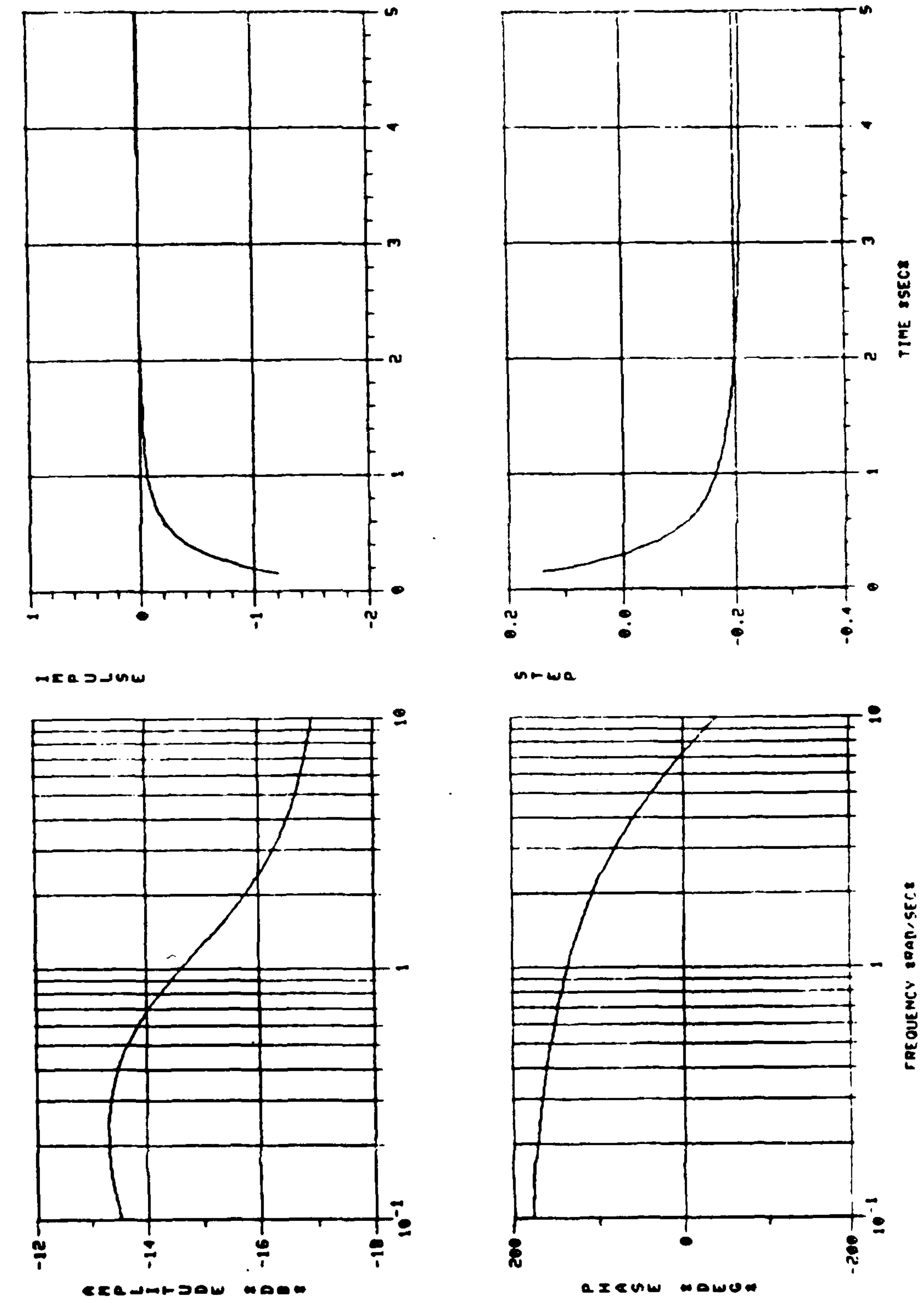
CASE 6 ALFA/STK FORCE 10 LB STEP





CASE 6 NZP/STK FORCE 10 LB STEP

CASE 6 NZCG/STK FORCE 10 LB STEP



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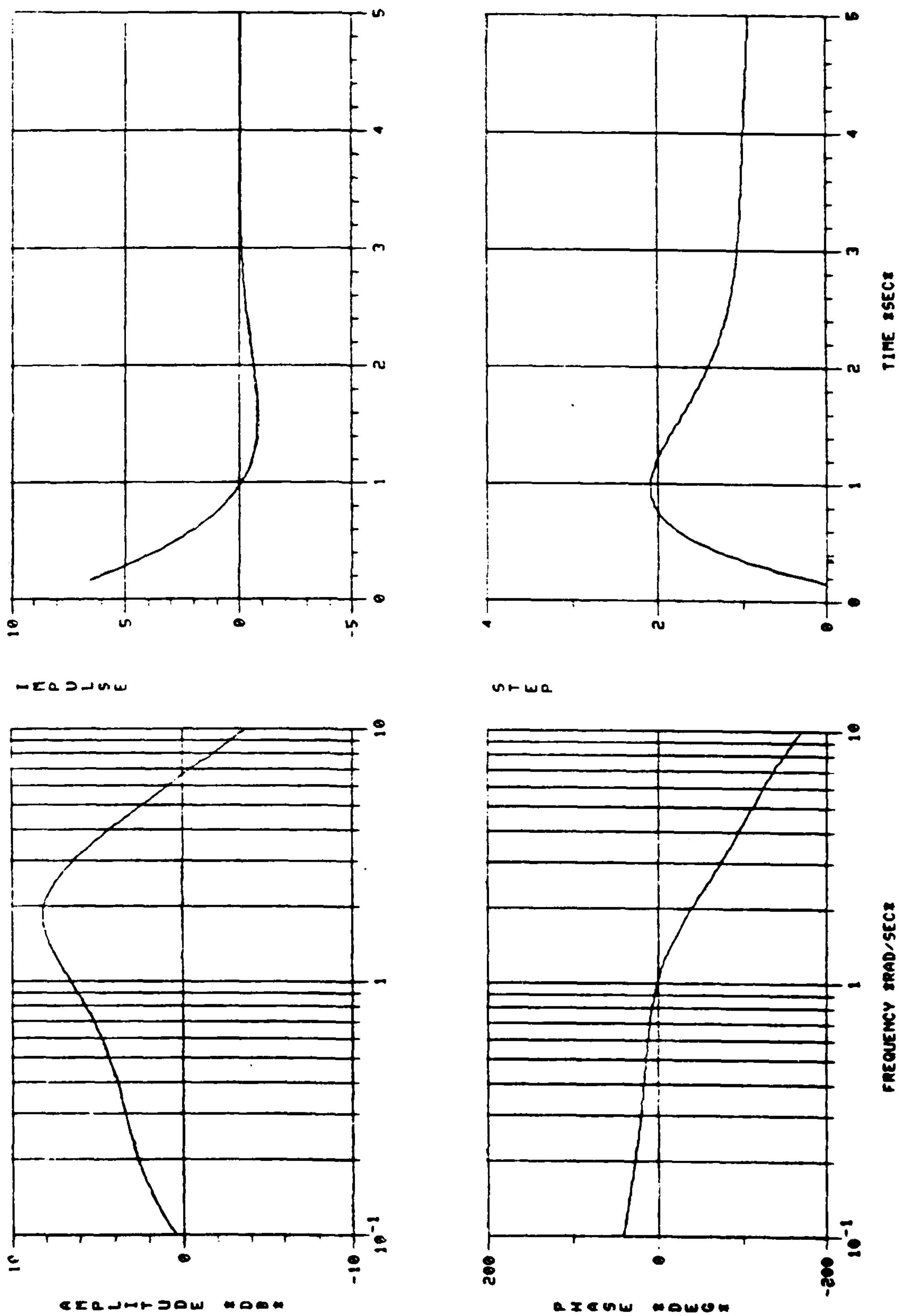

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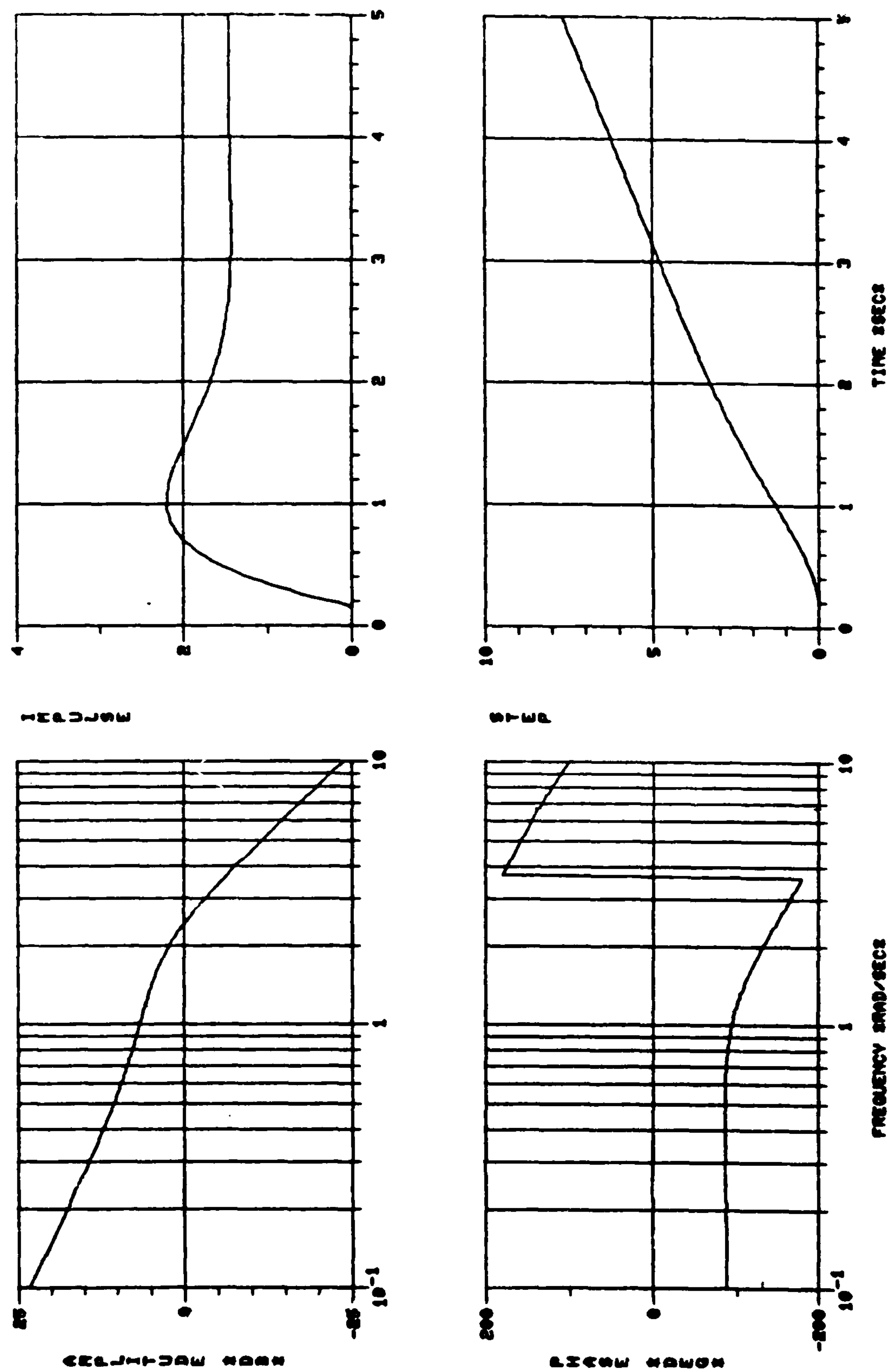

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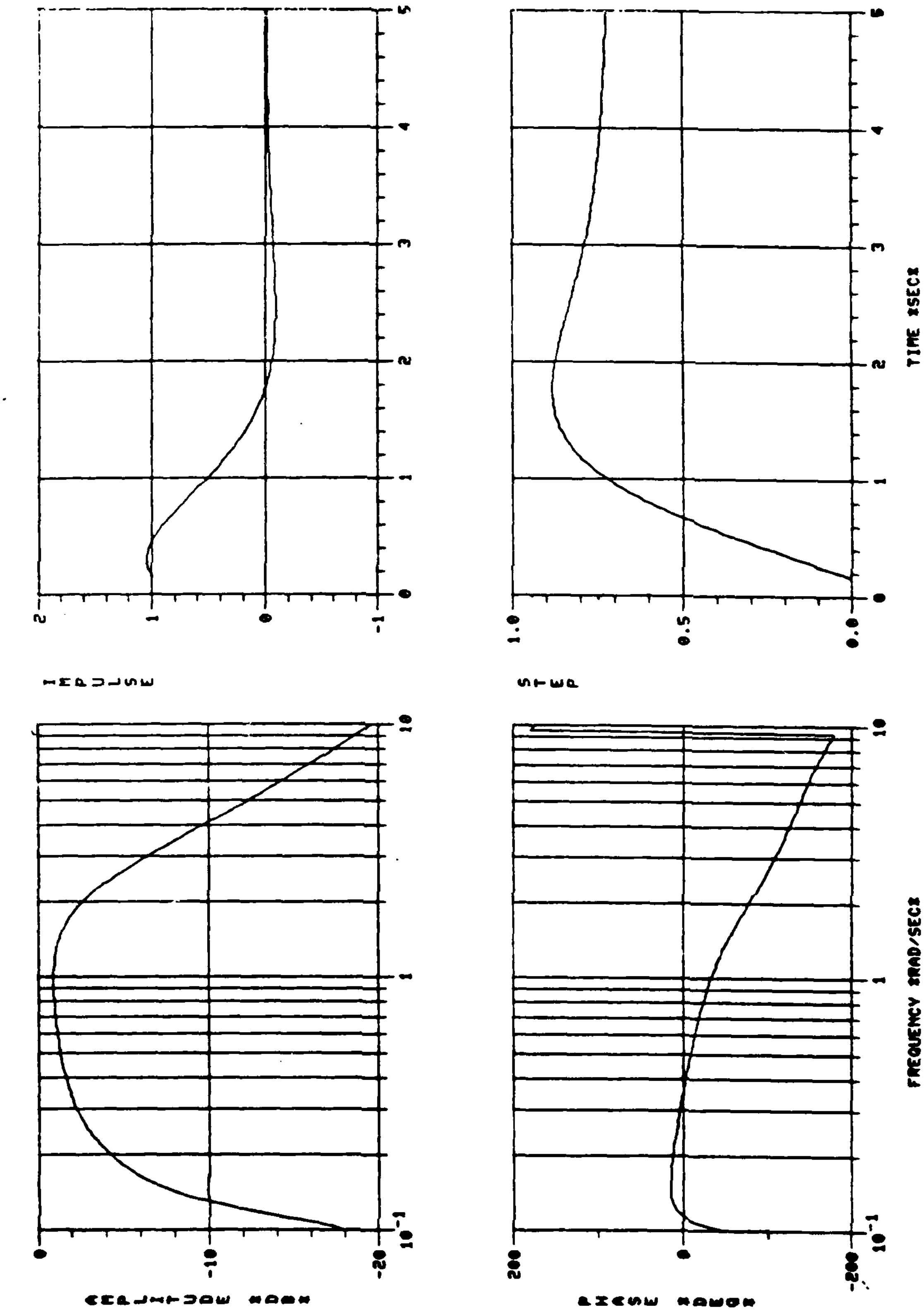

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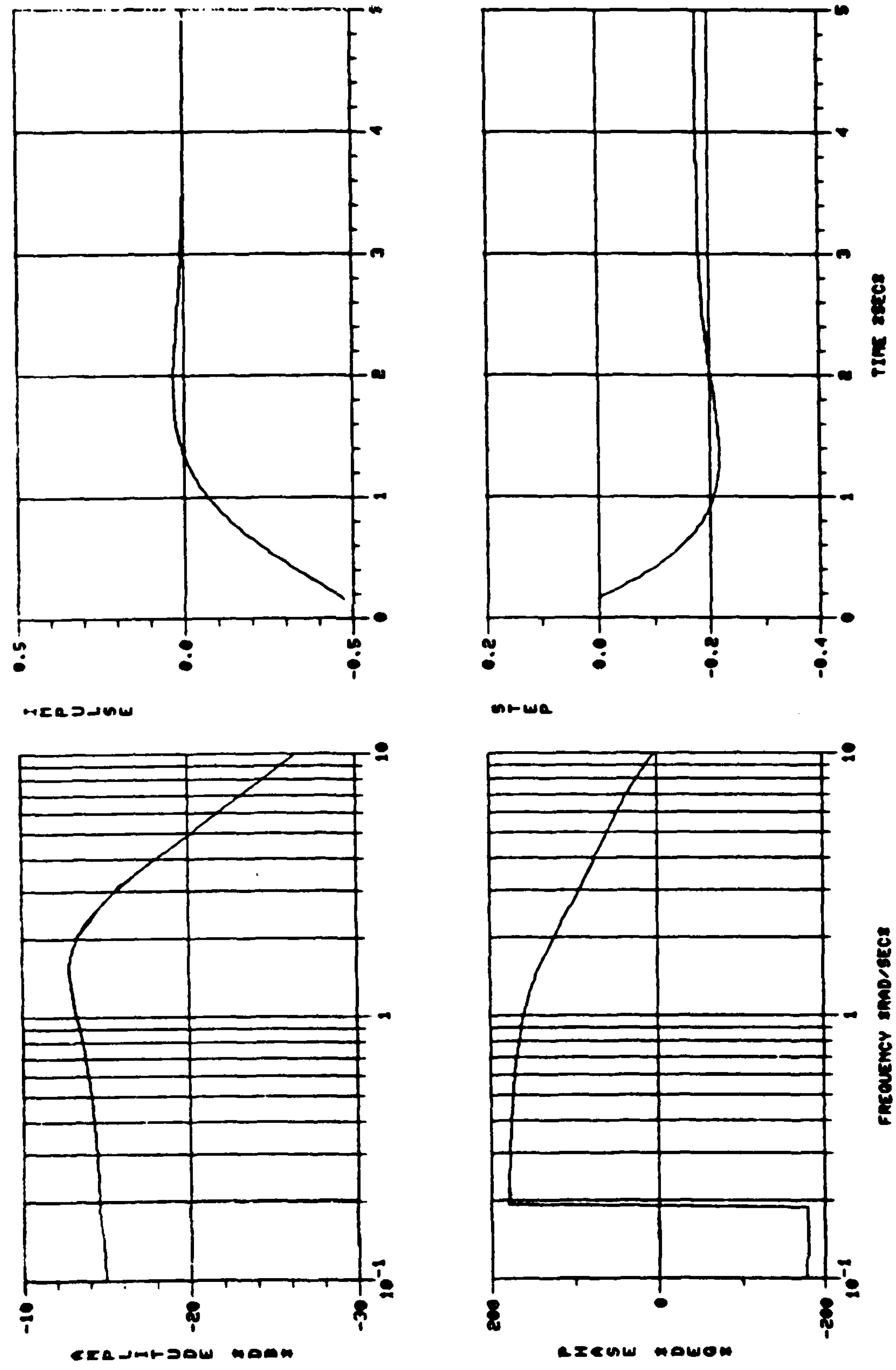

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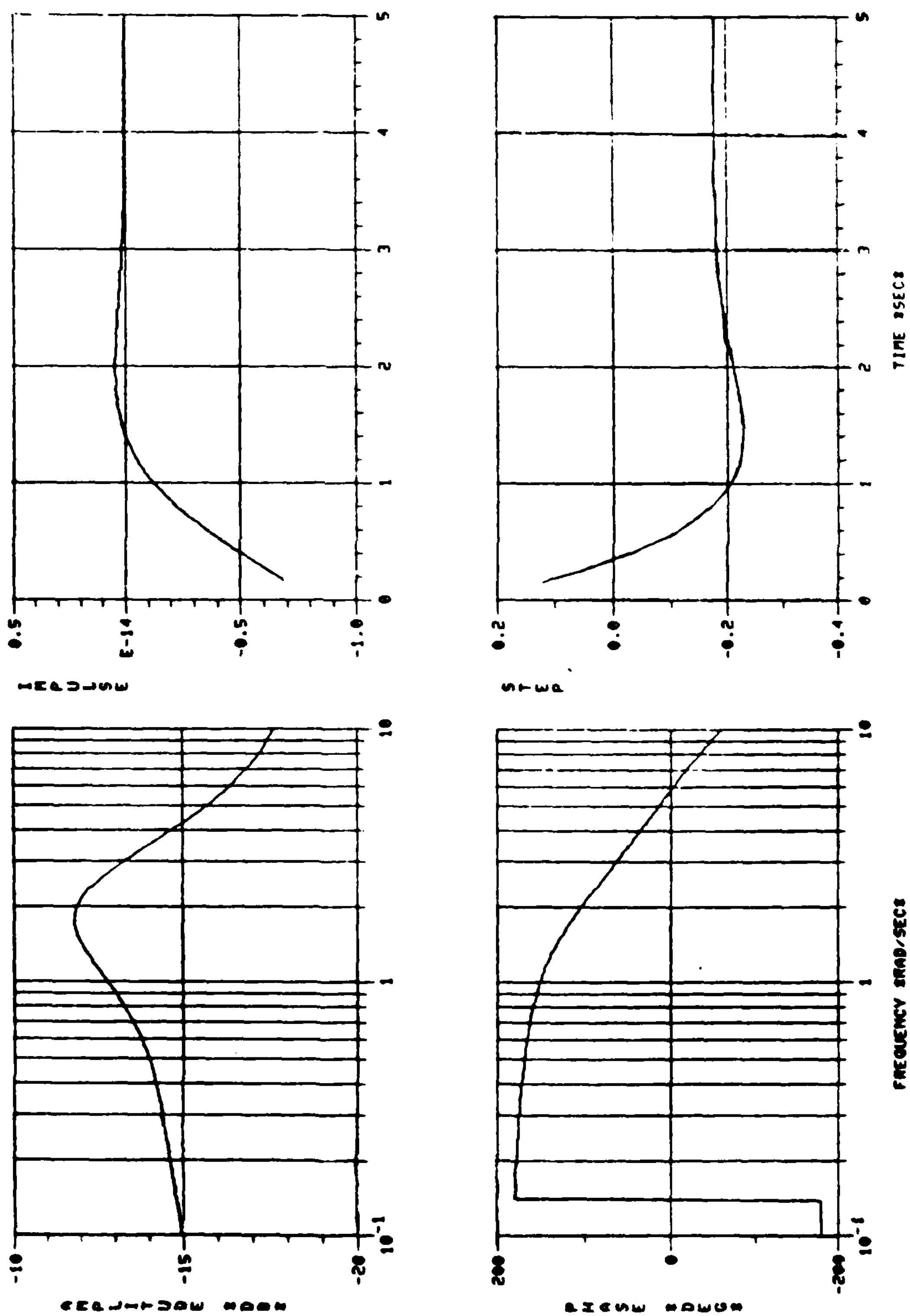
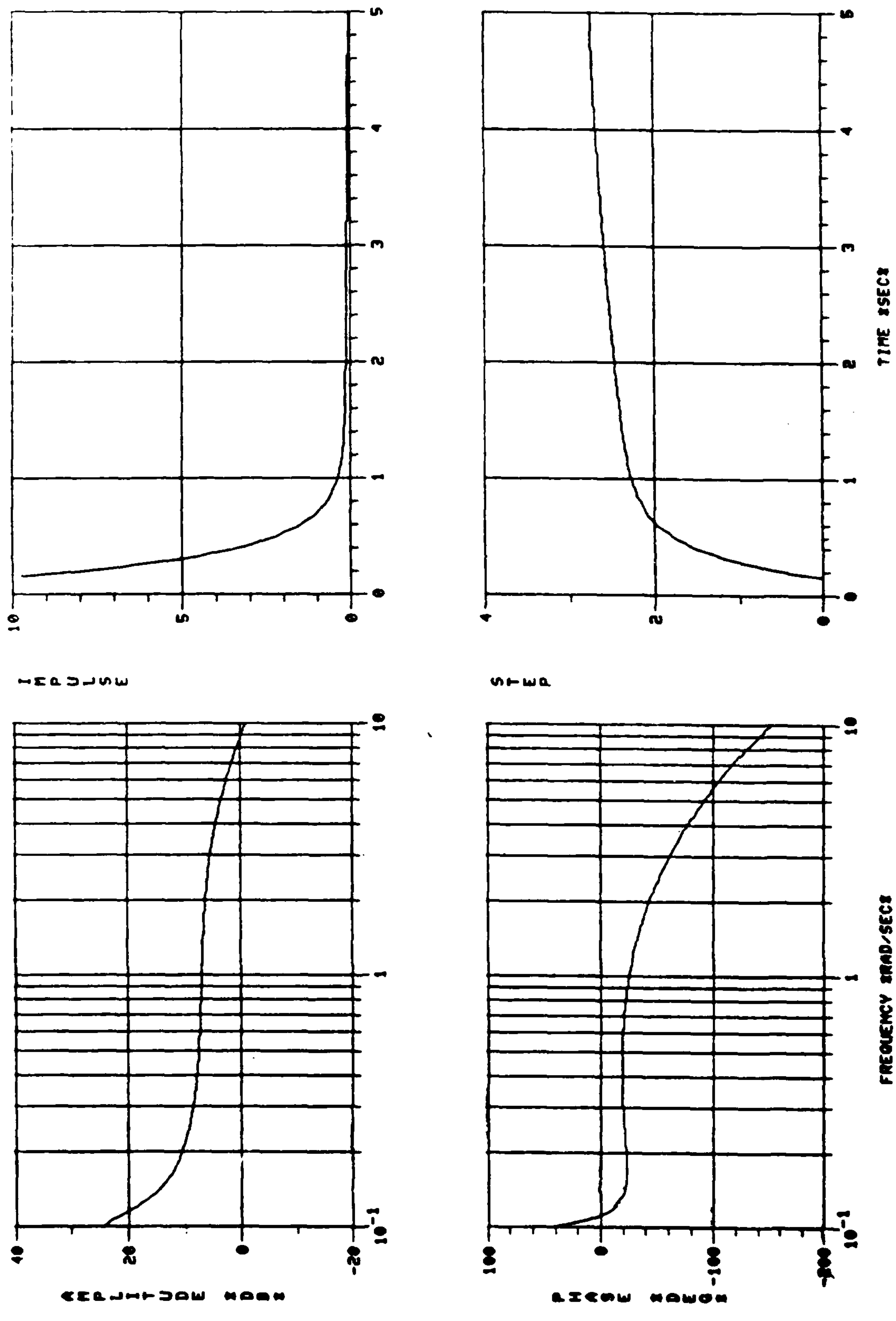
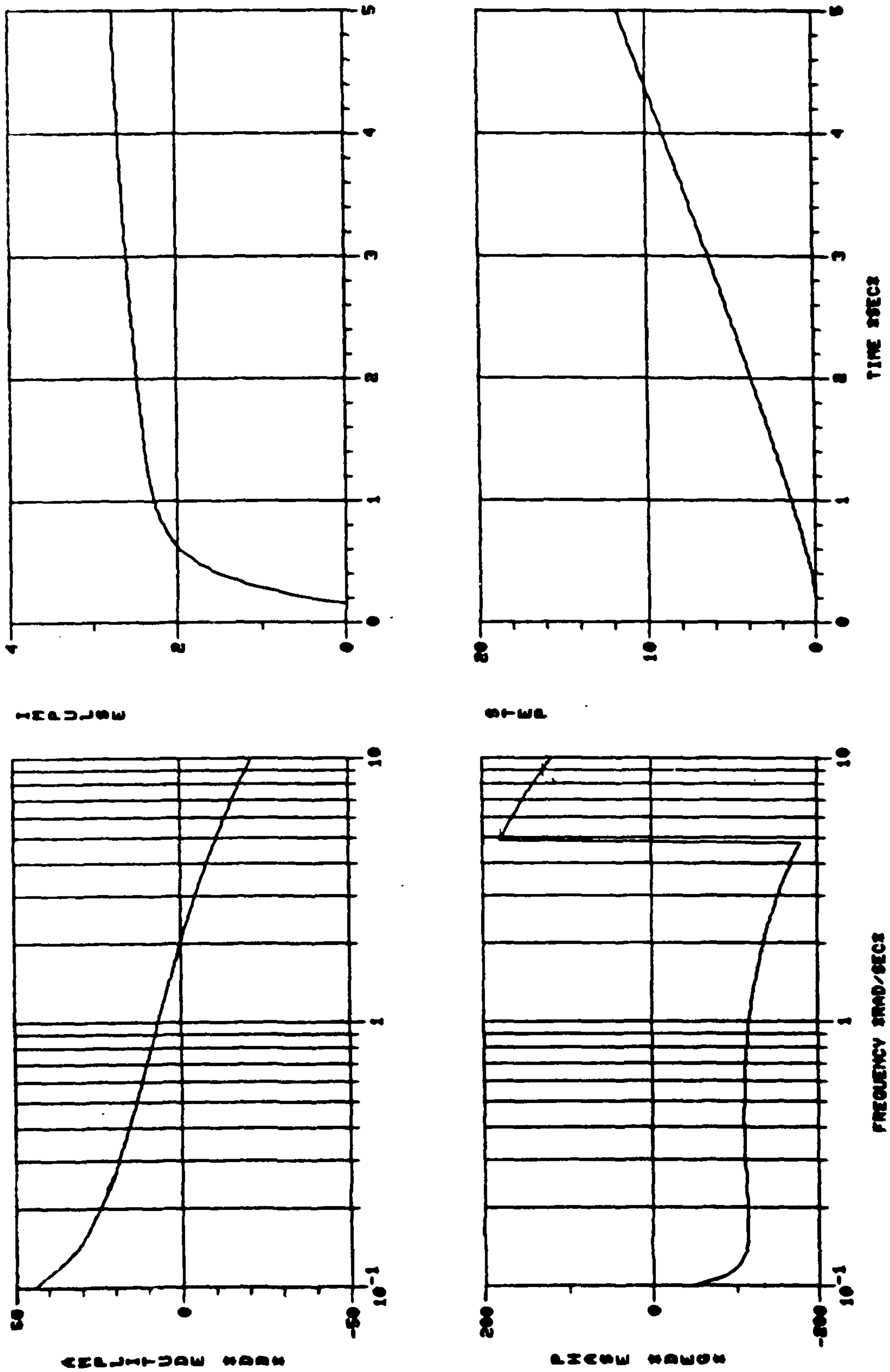




CASE 8 Q/STK FORCE 10 LB STEP

CASE 8 THETA/STK FORCE 10 LB STEP



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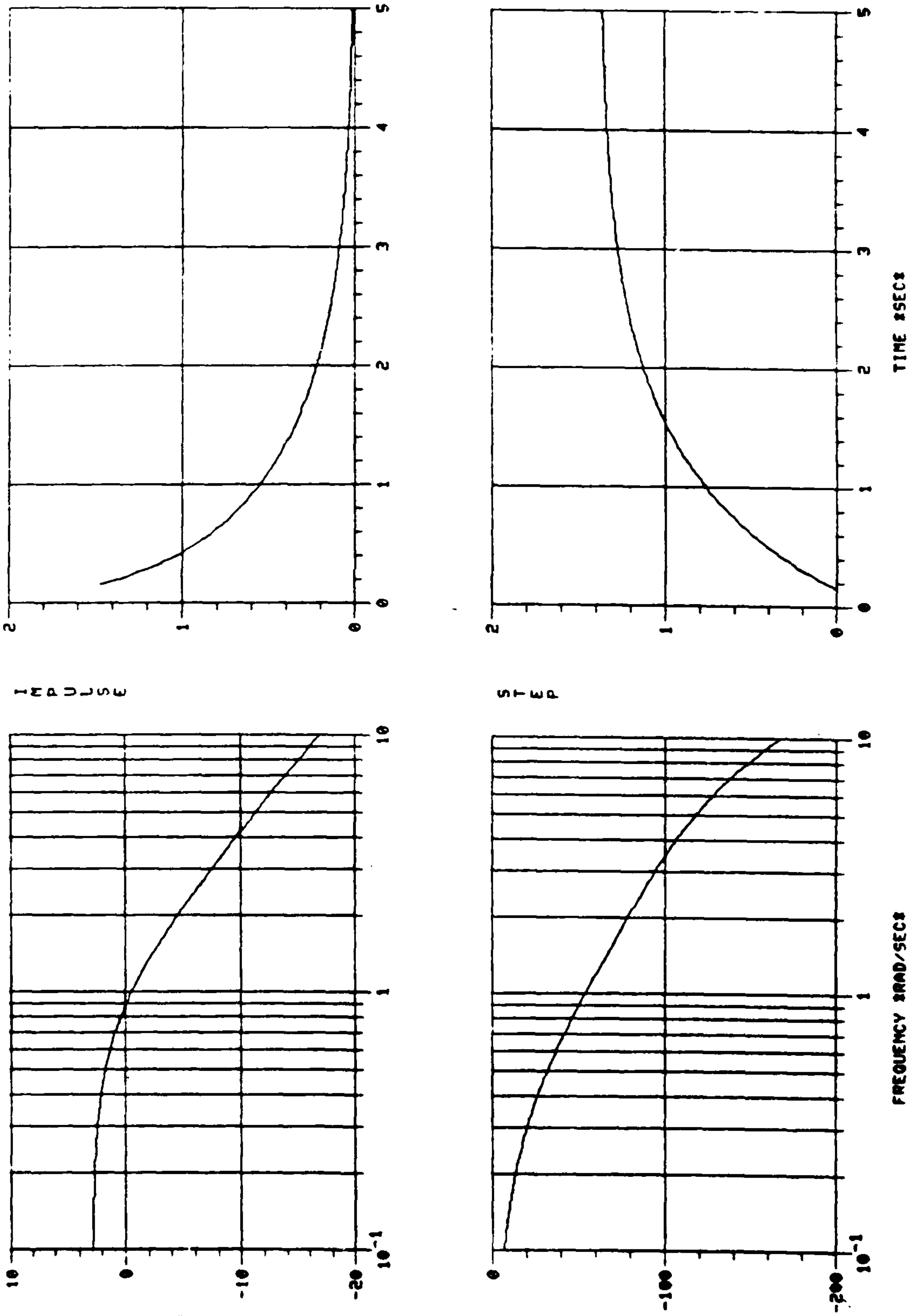

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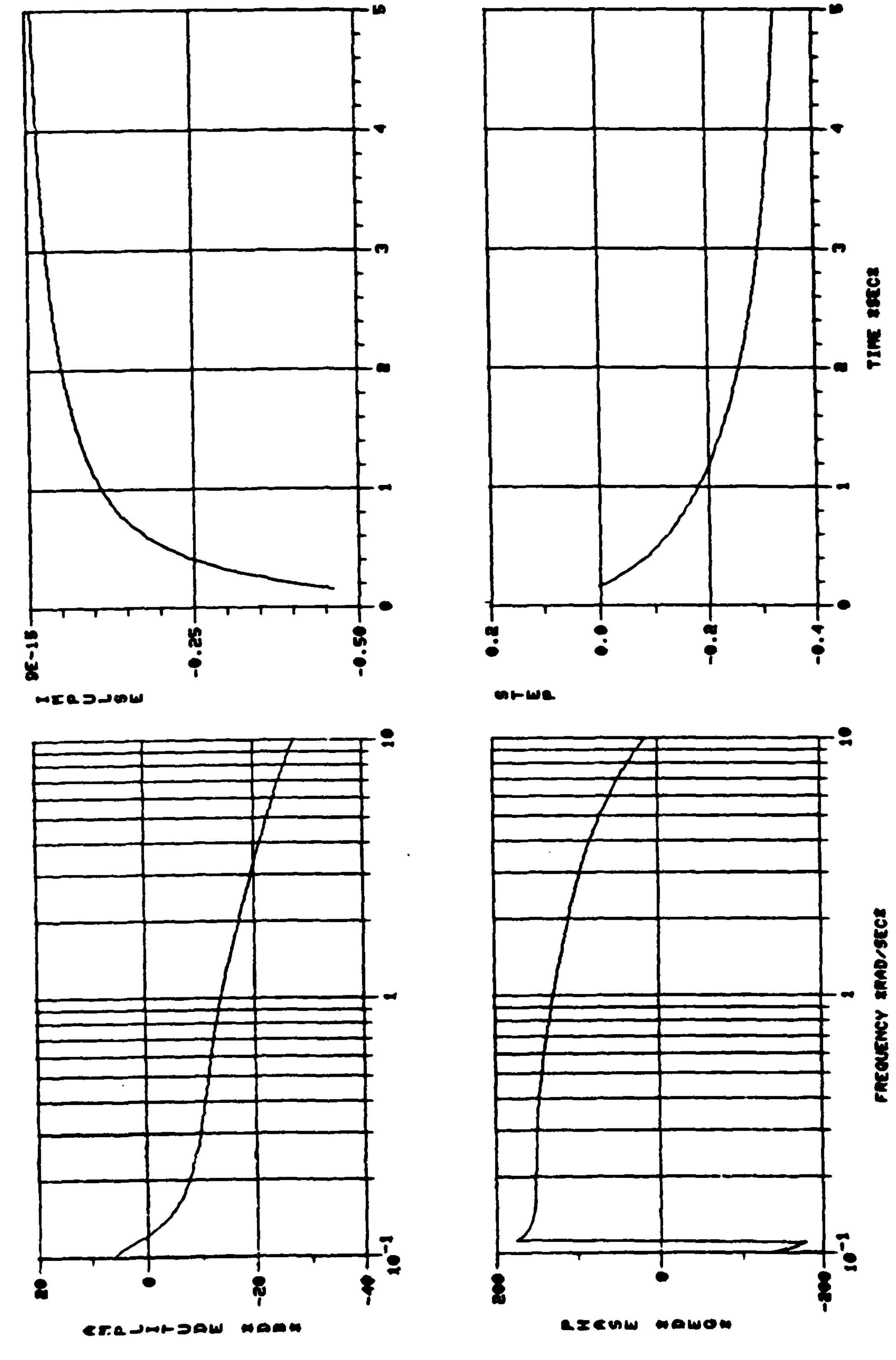

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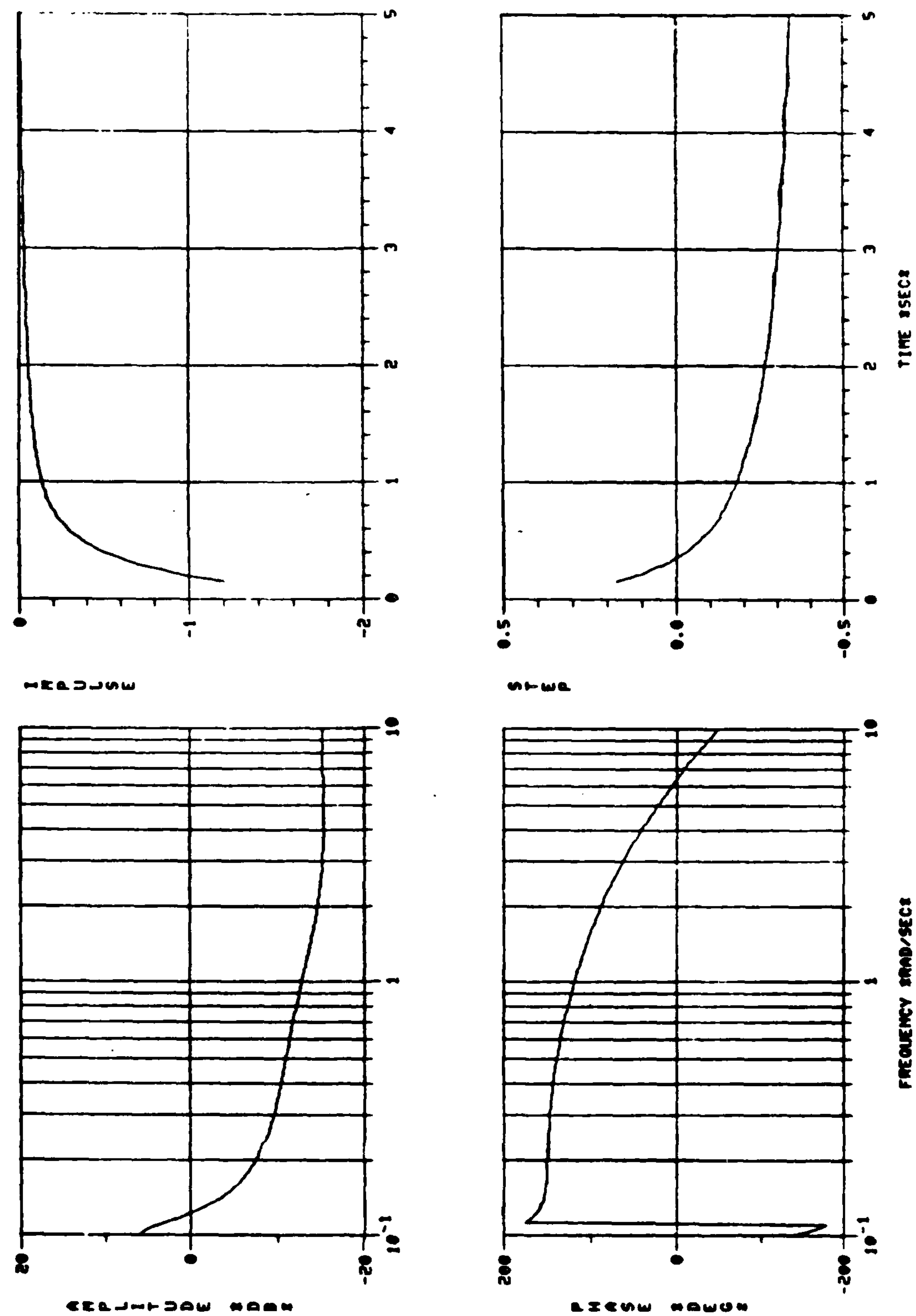
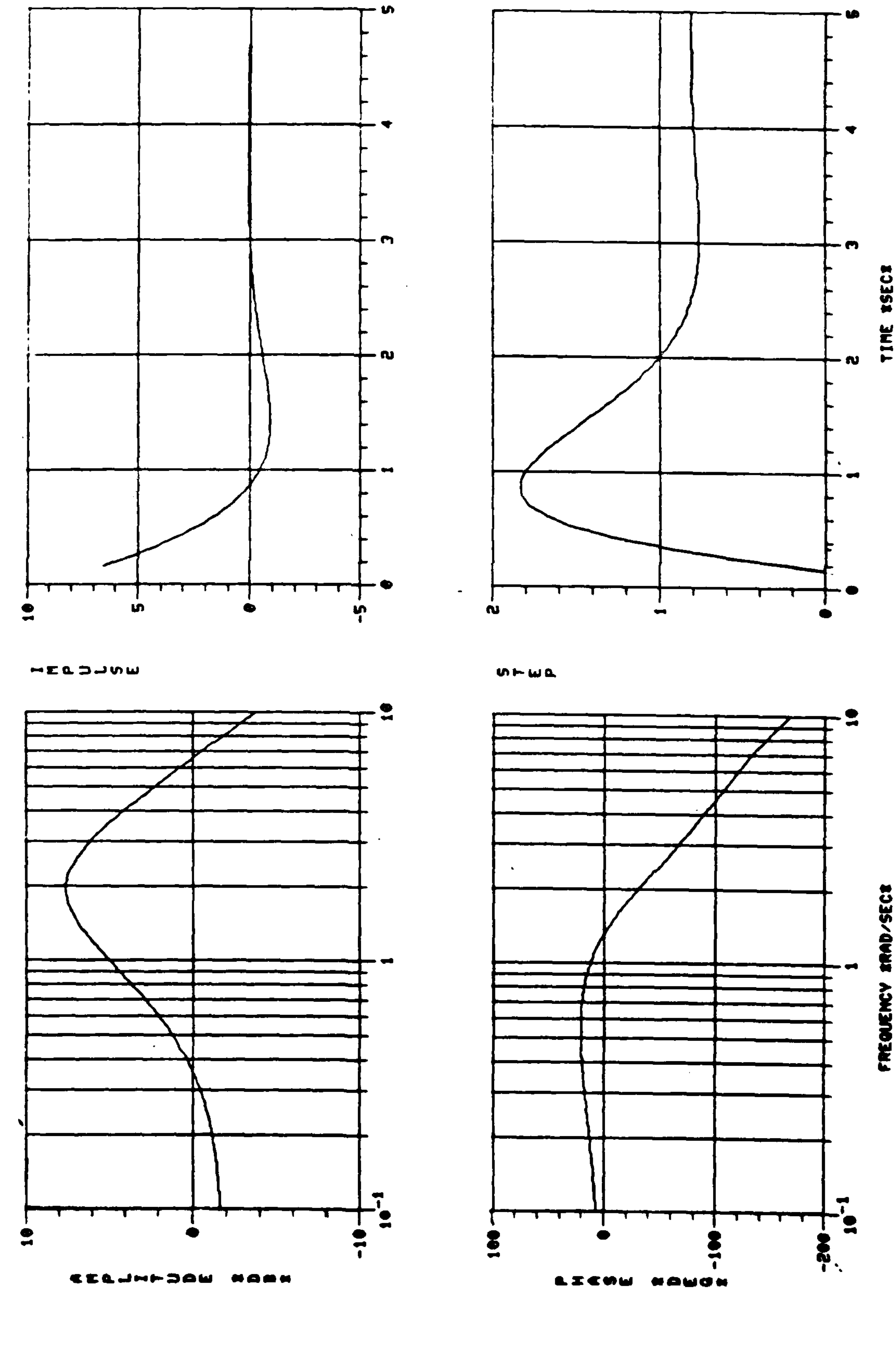
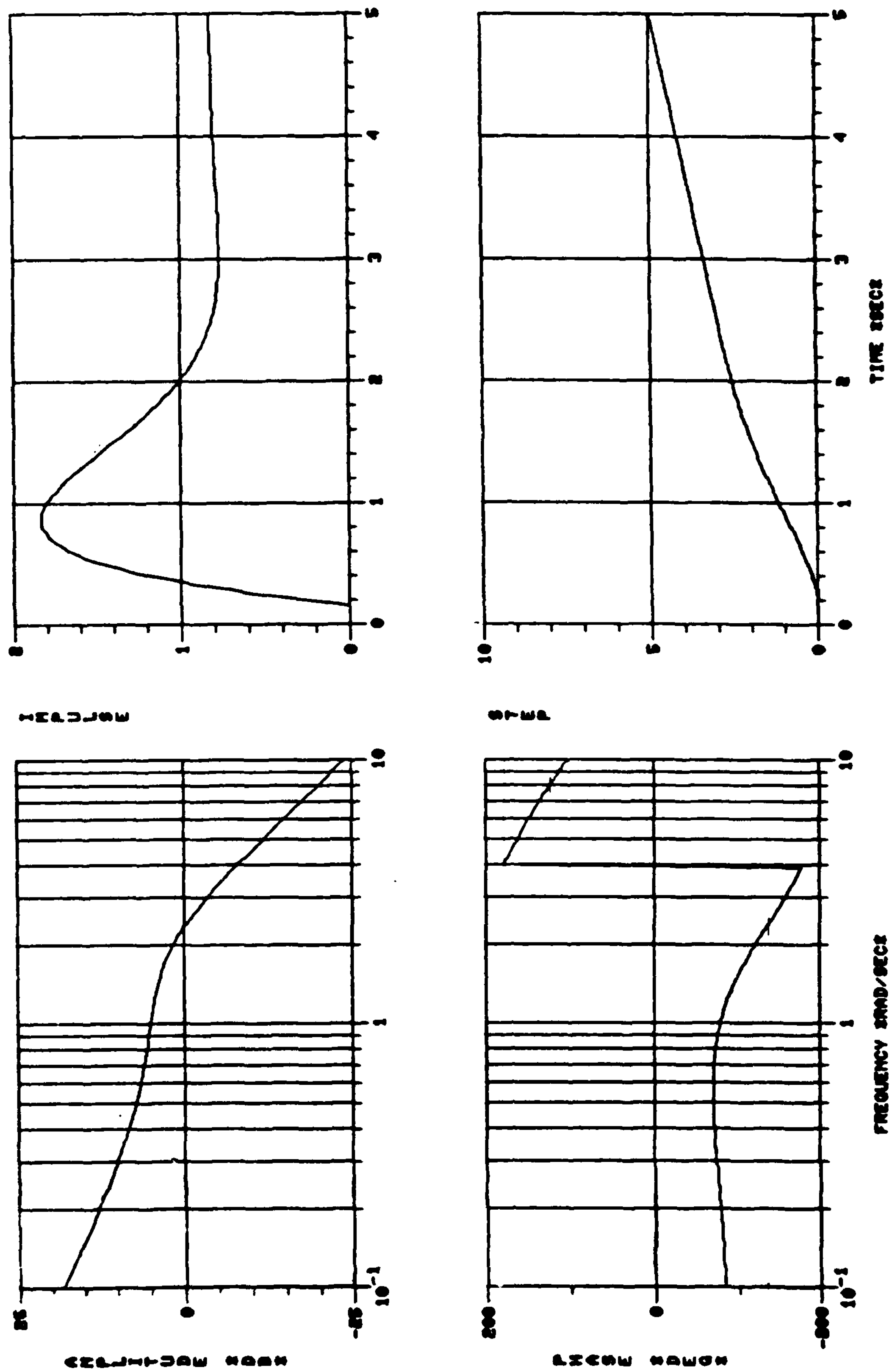


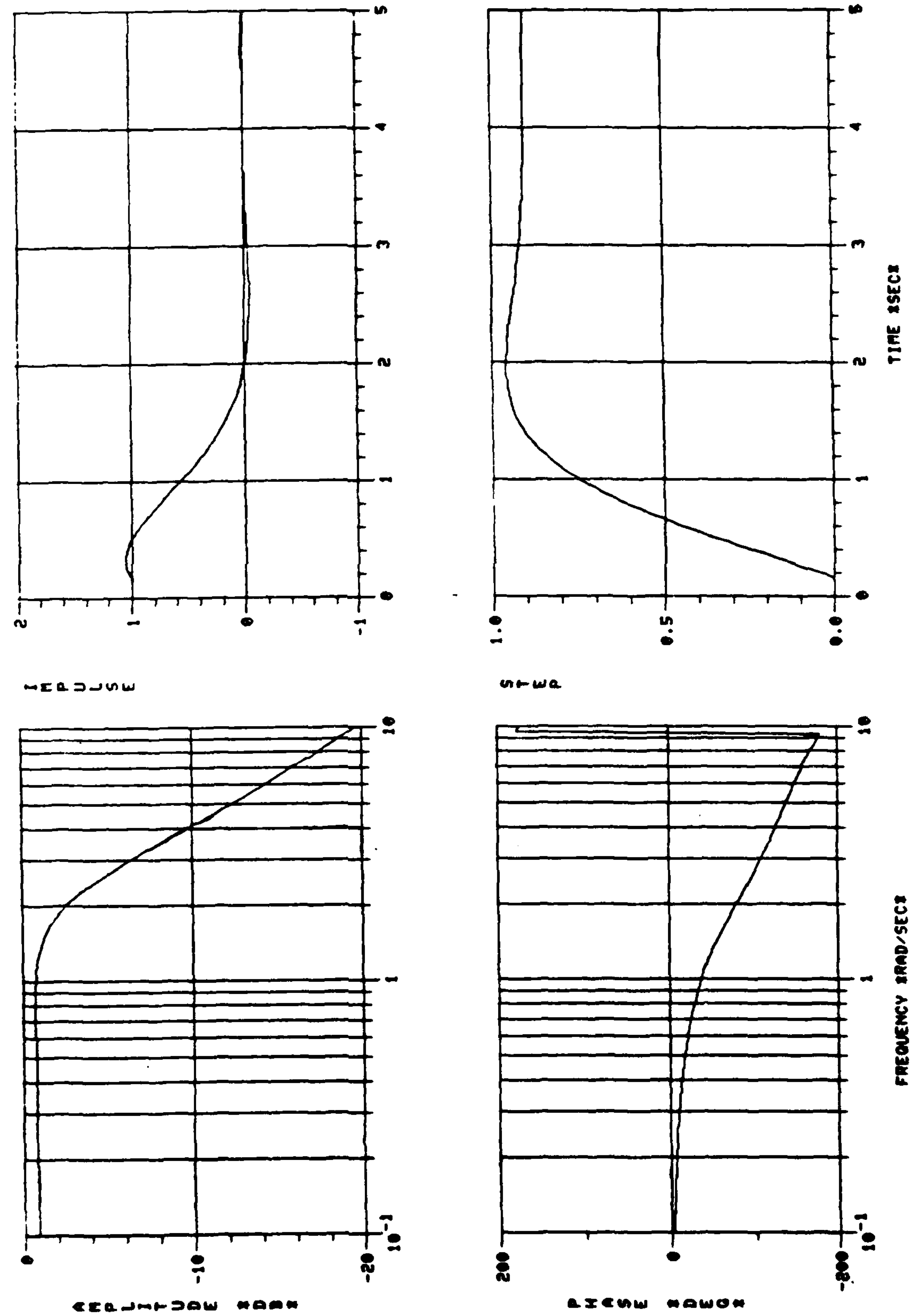
CASE 9 Q/STK FORCE 10 LB STEP

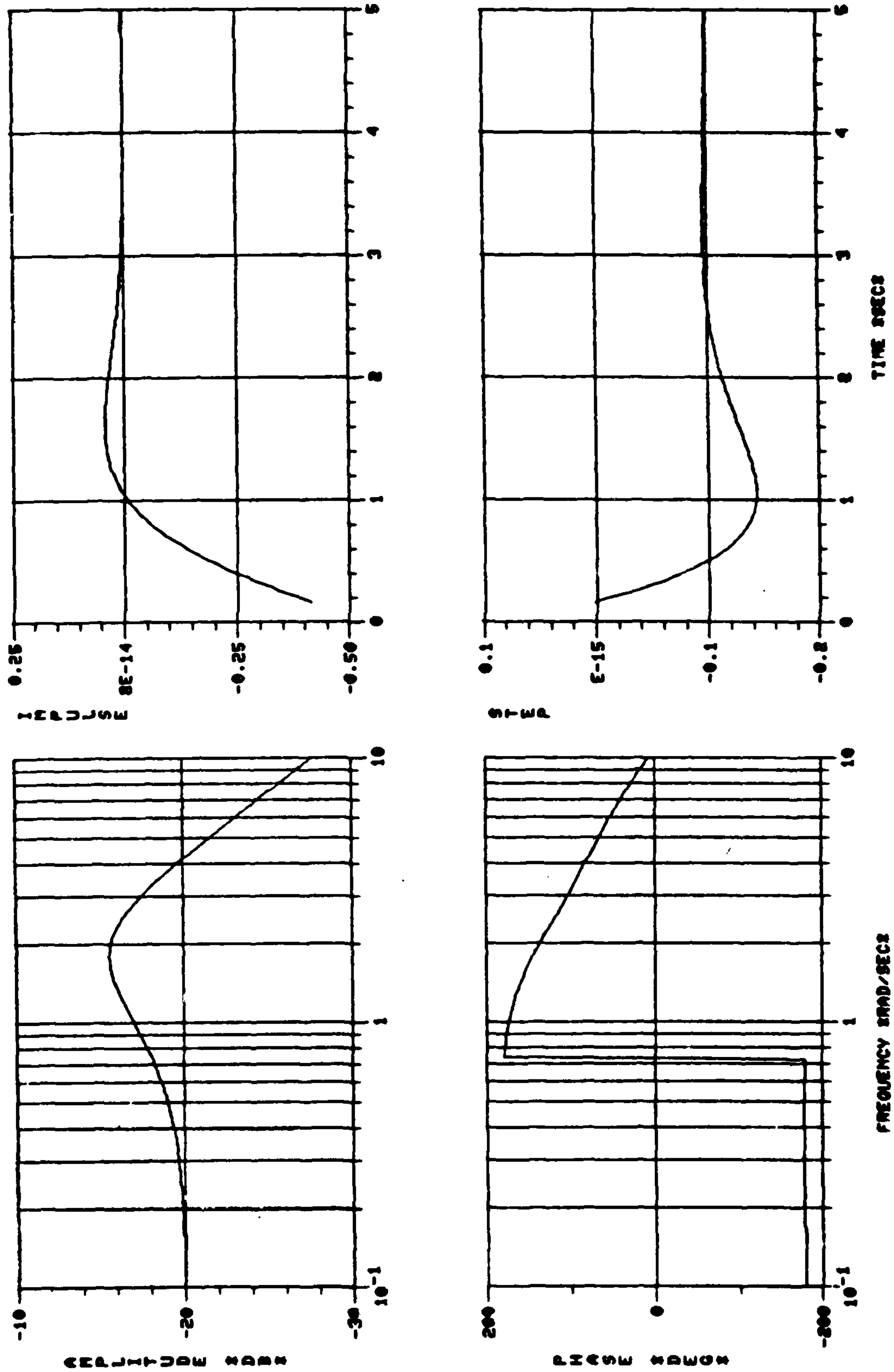




CASE 9 THETA/STK FORCE 10 LB STEP

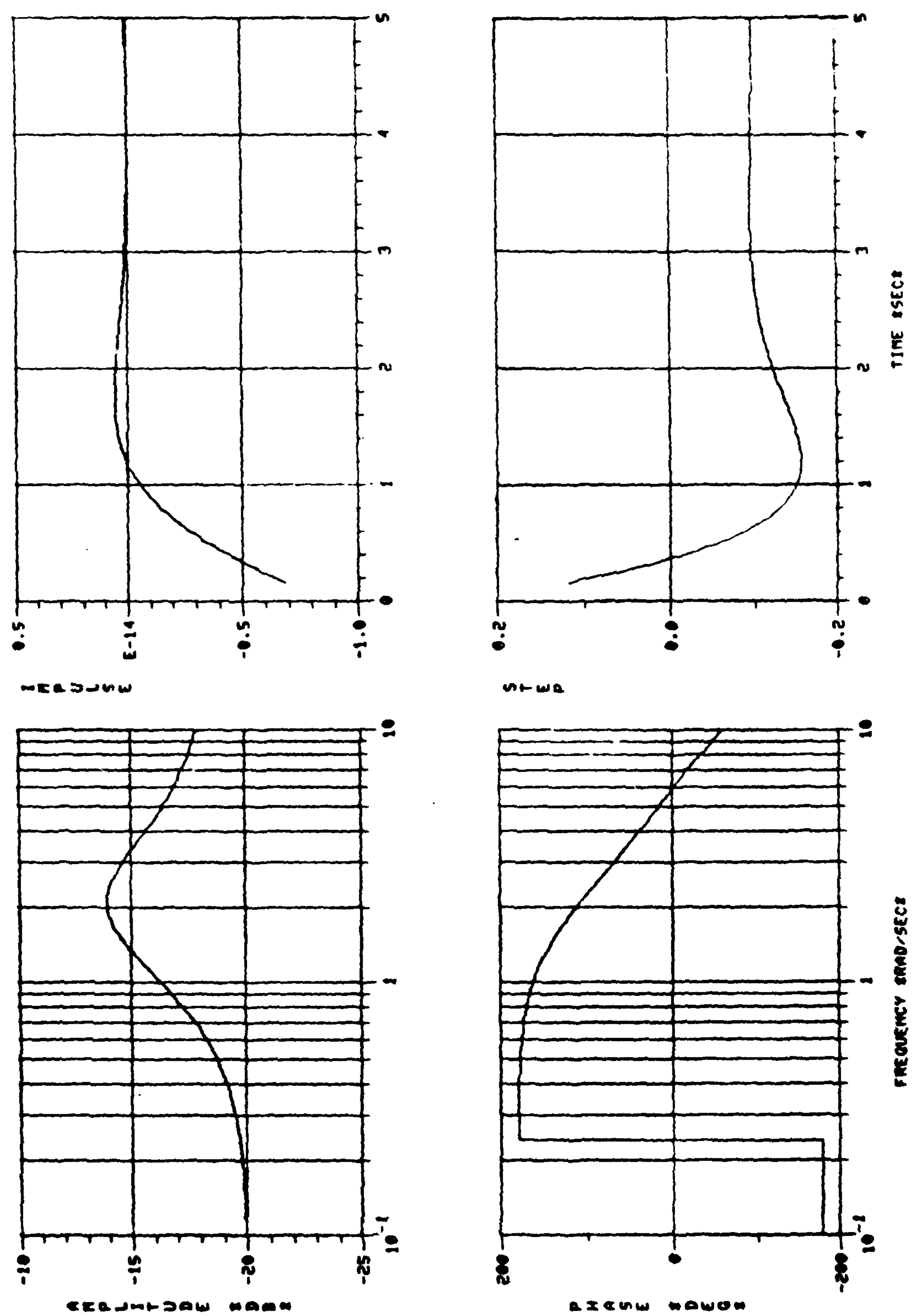
CASE 9 ALFA/STK FORCE 10 LB STEP



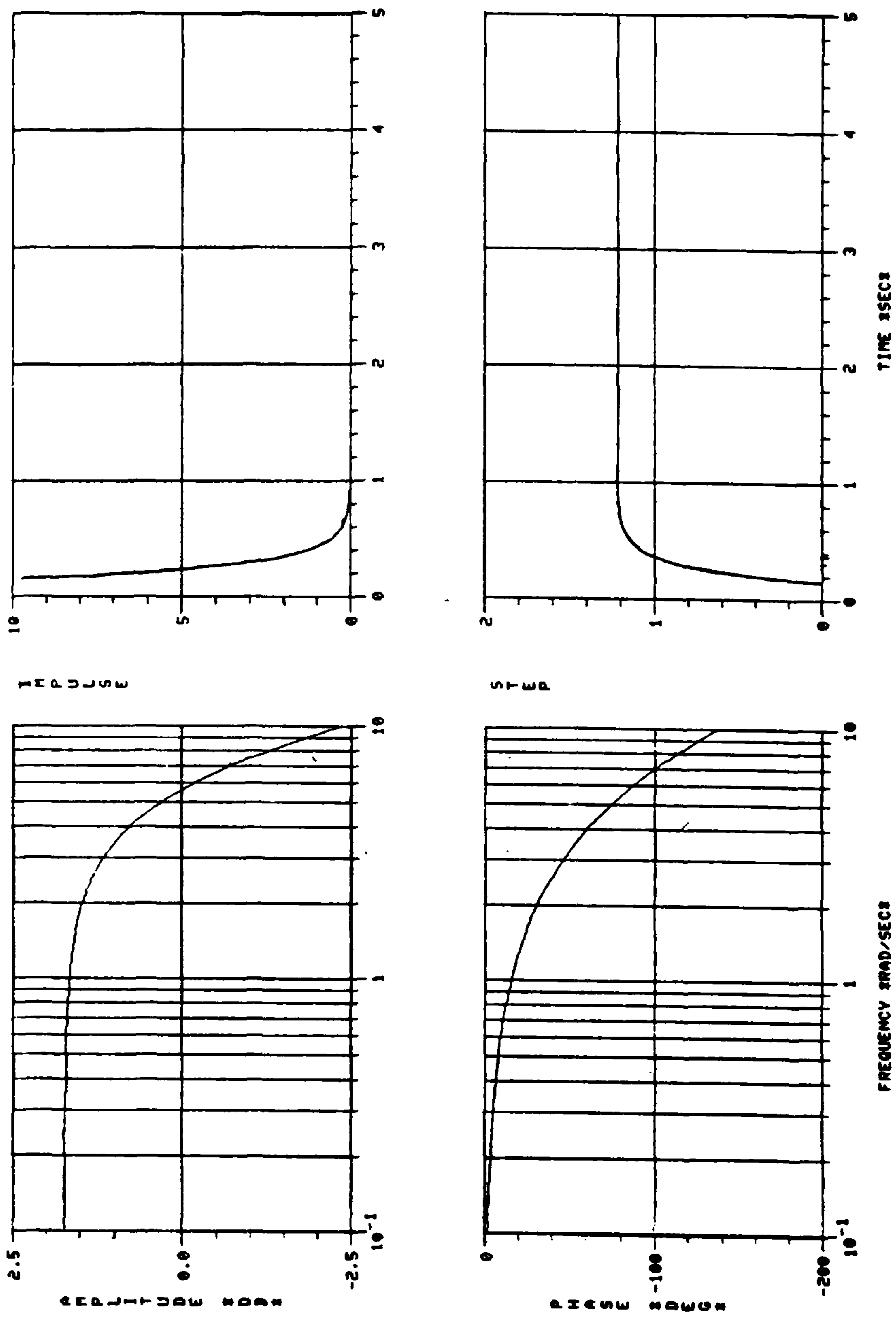


CASE 9 NZP/STK FORCE 10 LB STEP

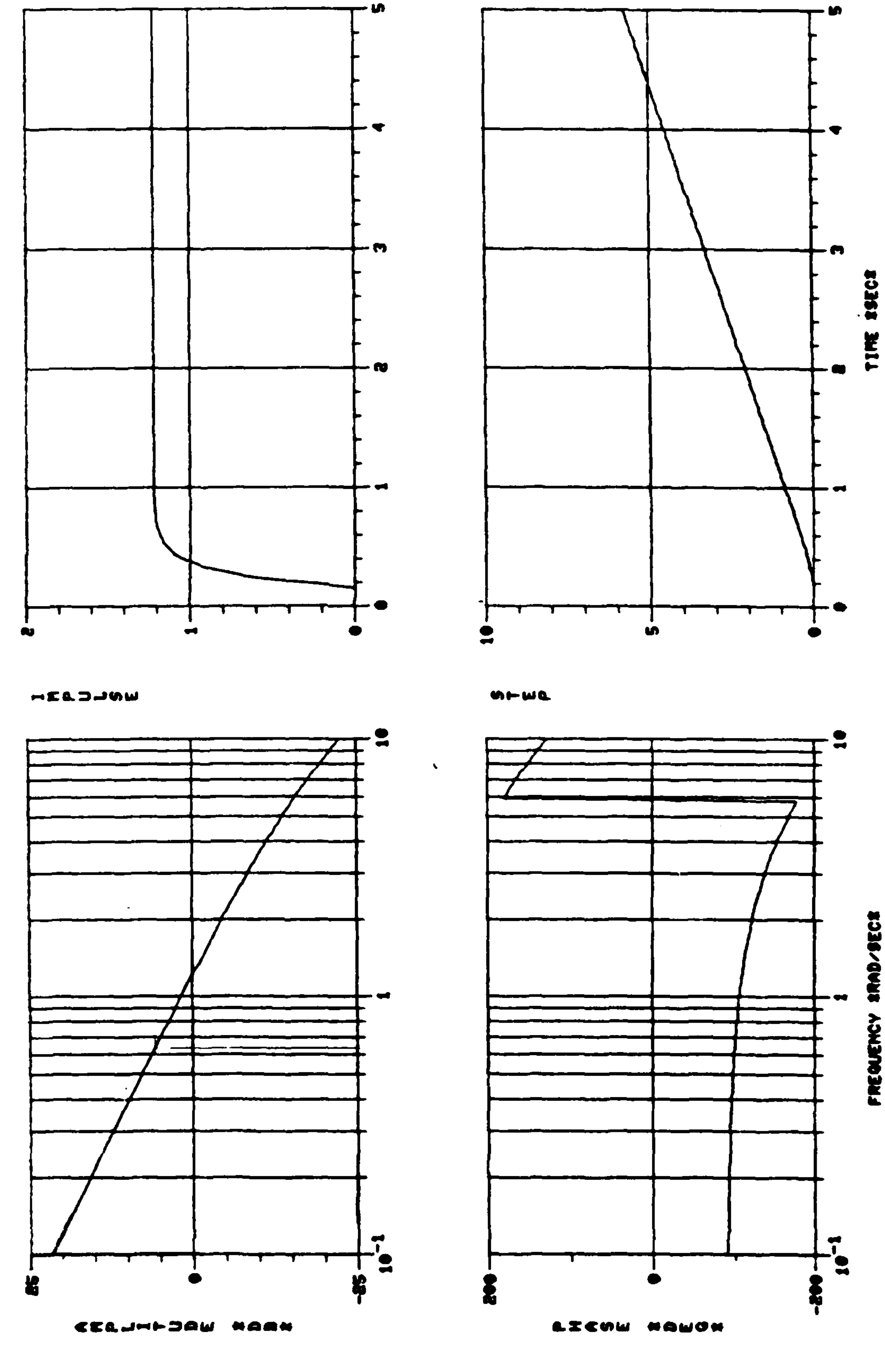
CASE 9 NZCG/STK FORCE 10 LB STEP



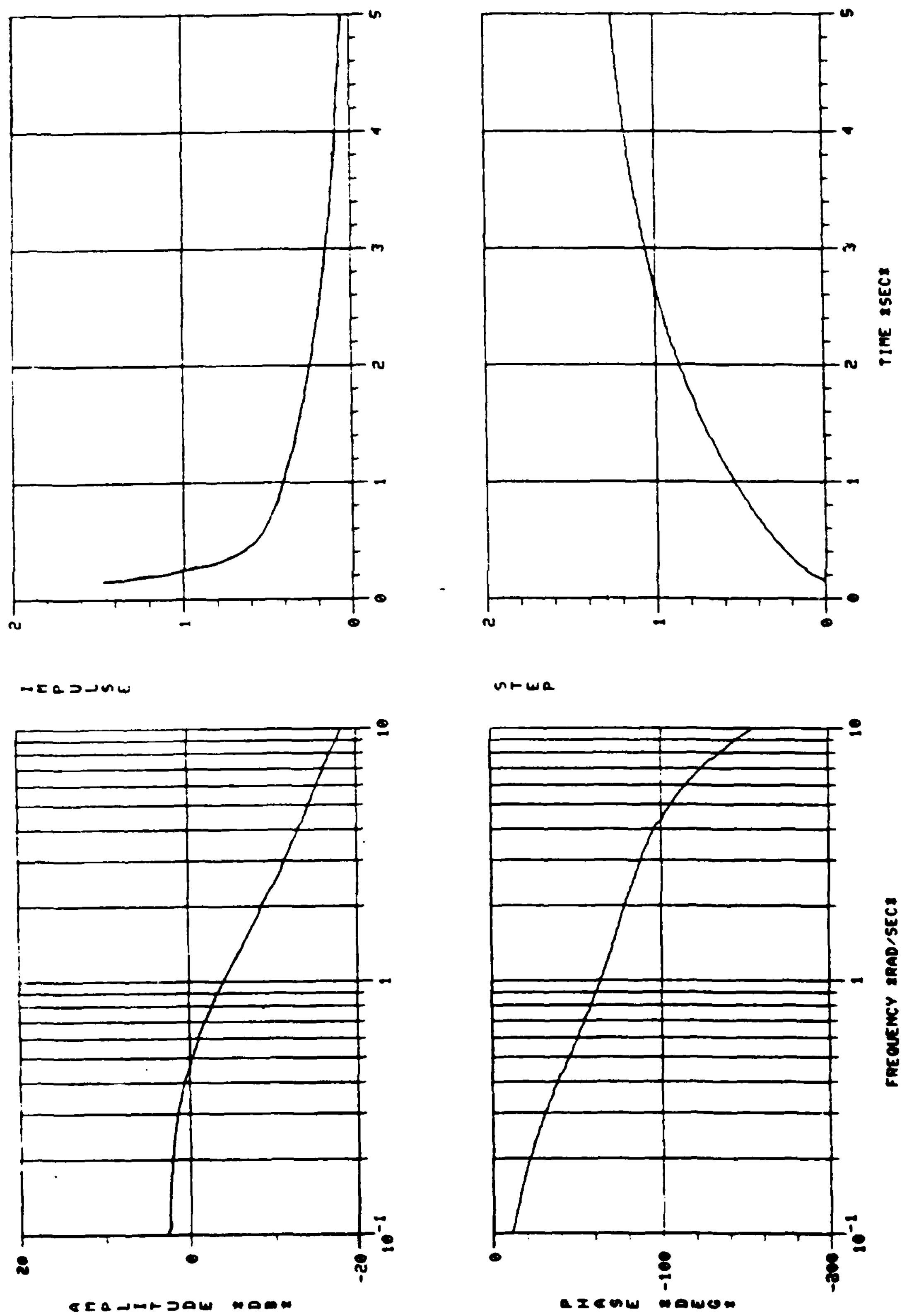
CASE 10 Q/STK FORCE 10 LB STEP



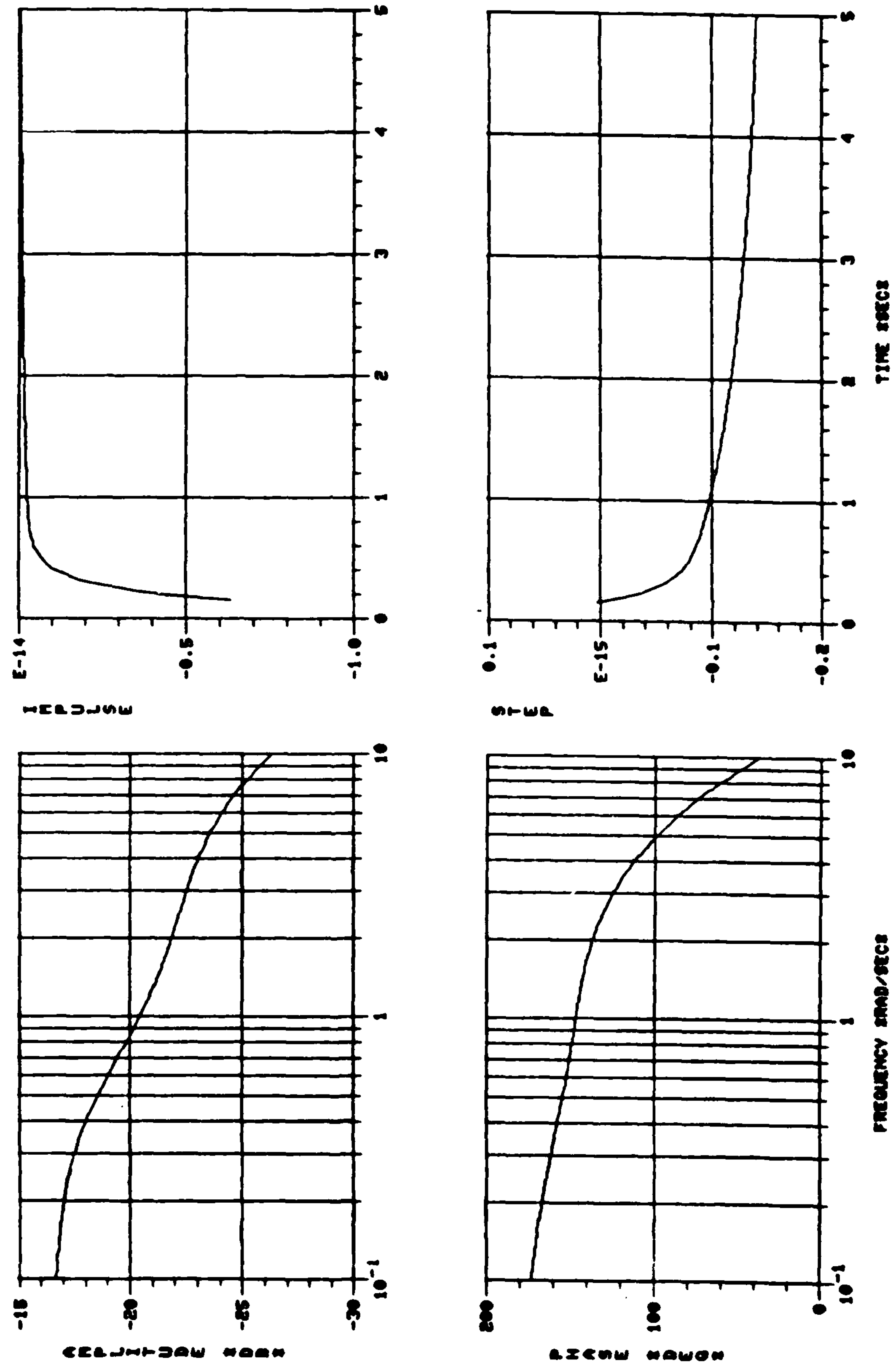
CASE 10 THETA/STK FORCE 10 LB STEP



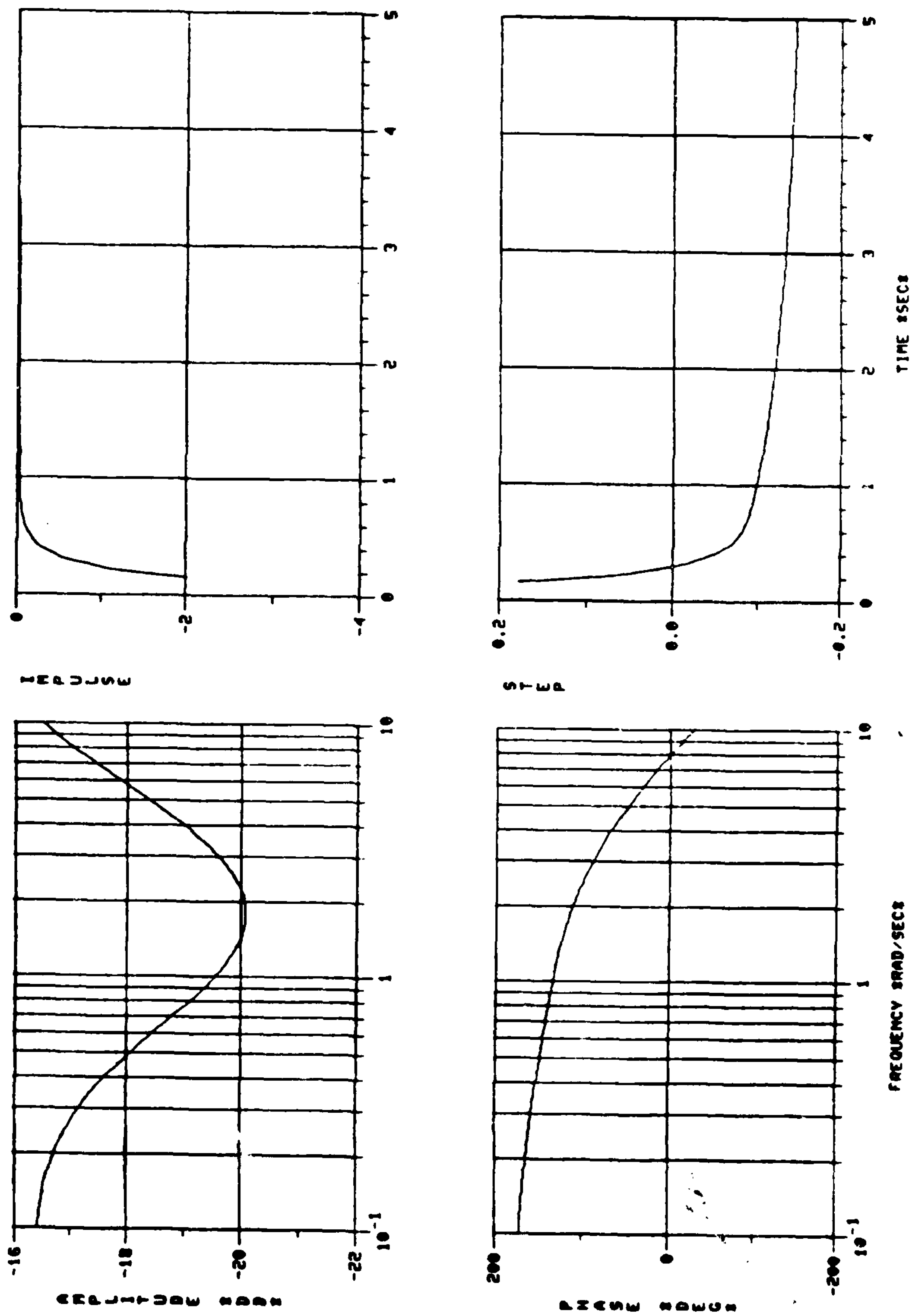
CASE 10 ALFA/STK FORCE 10 LB STEP



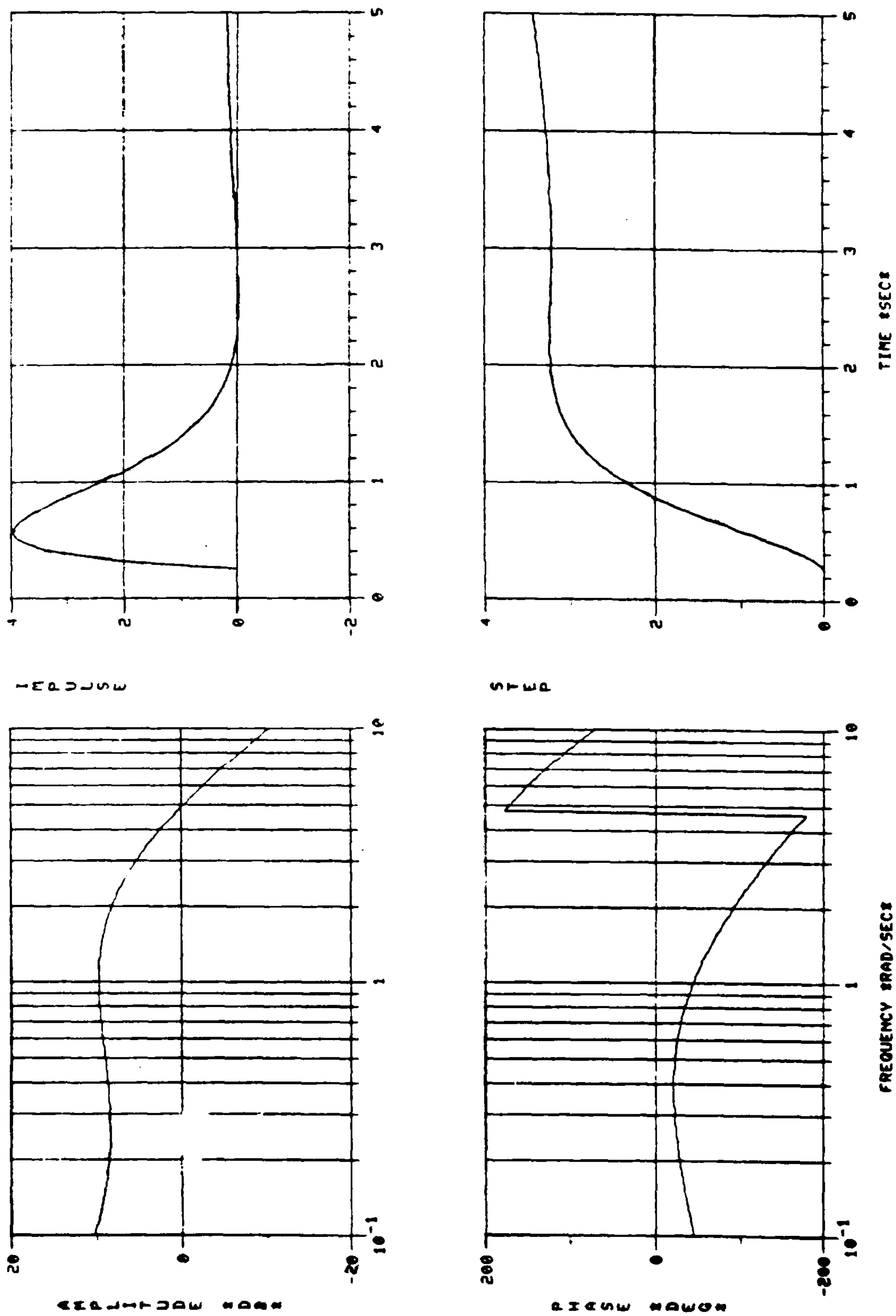
CASE 10 NZP/STK FORCE 10 LB STEP



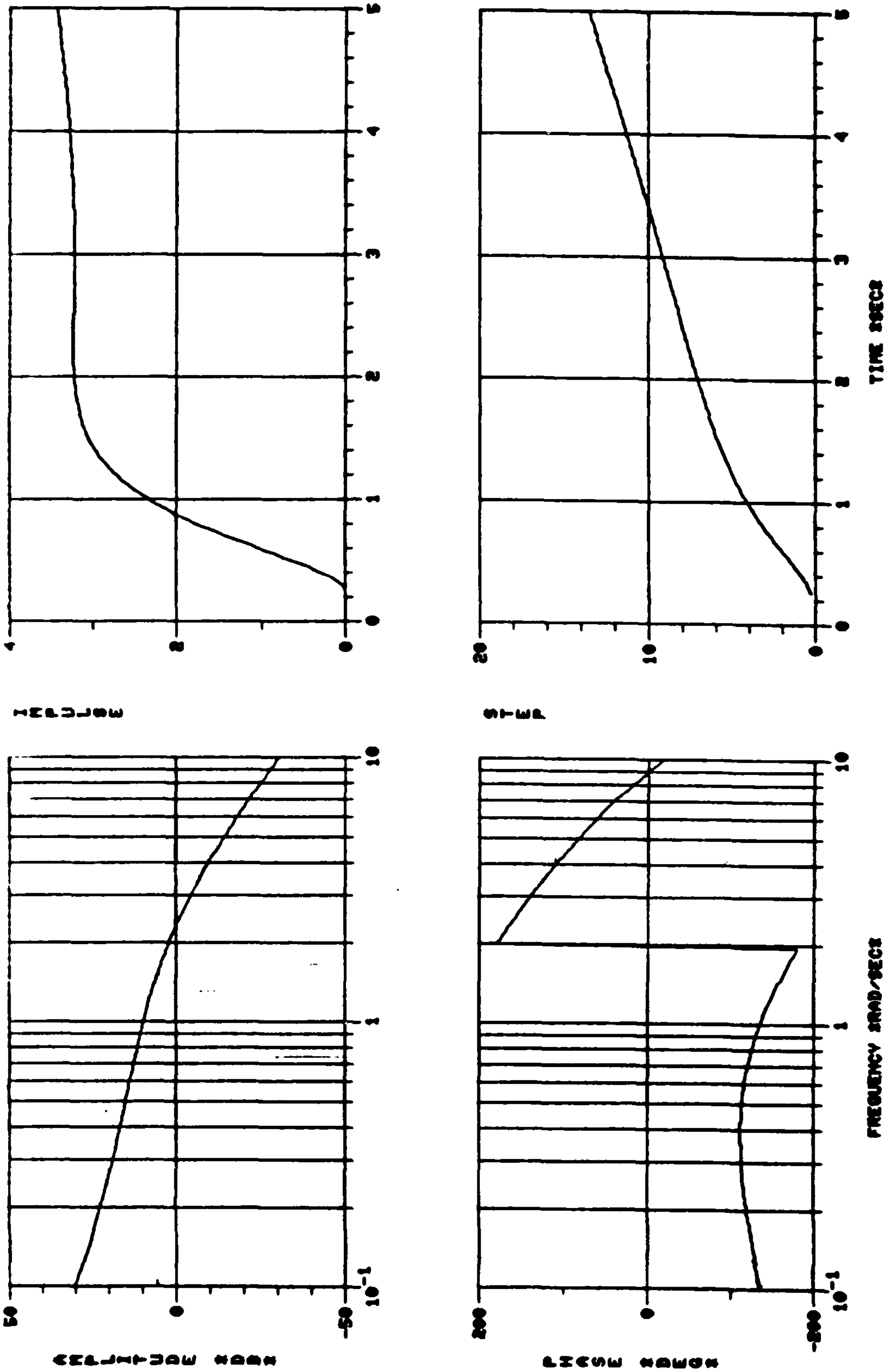
CASE 10 NZCG/STK FORCE 10 LB STEP



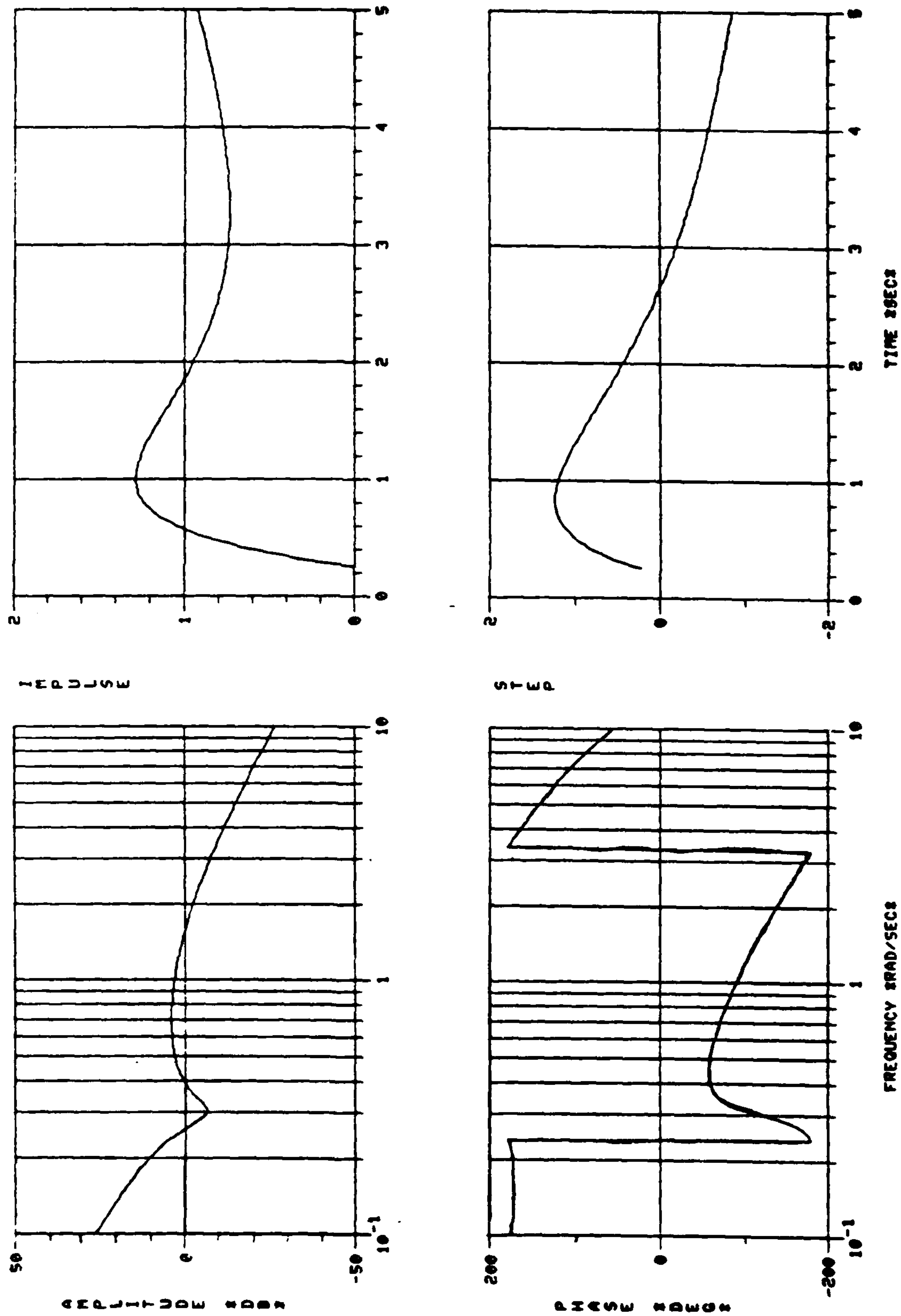
CASE 11 Q/STK FORCE 10 LB STEP



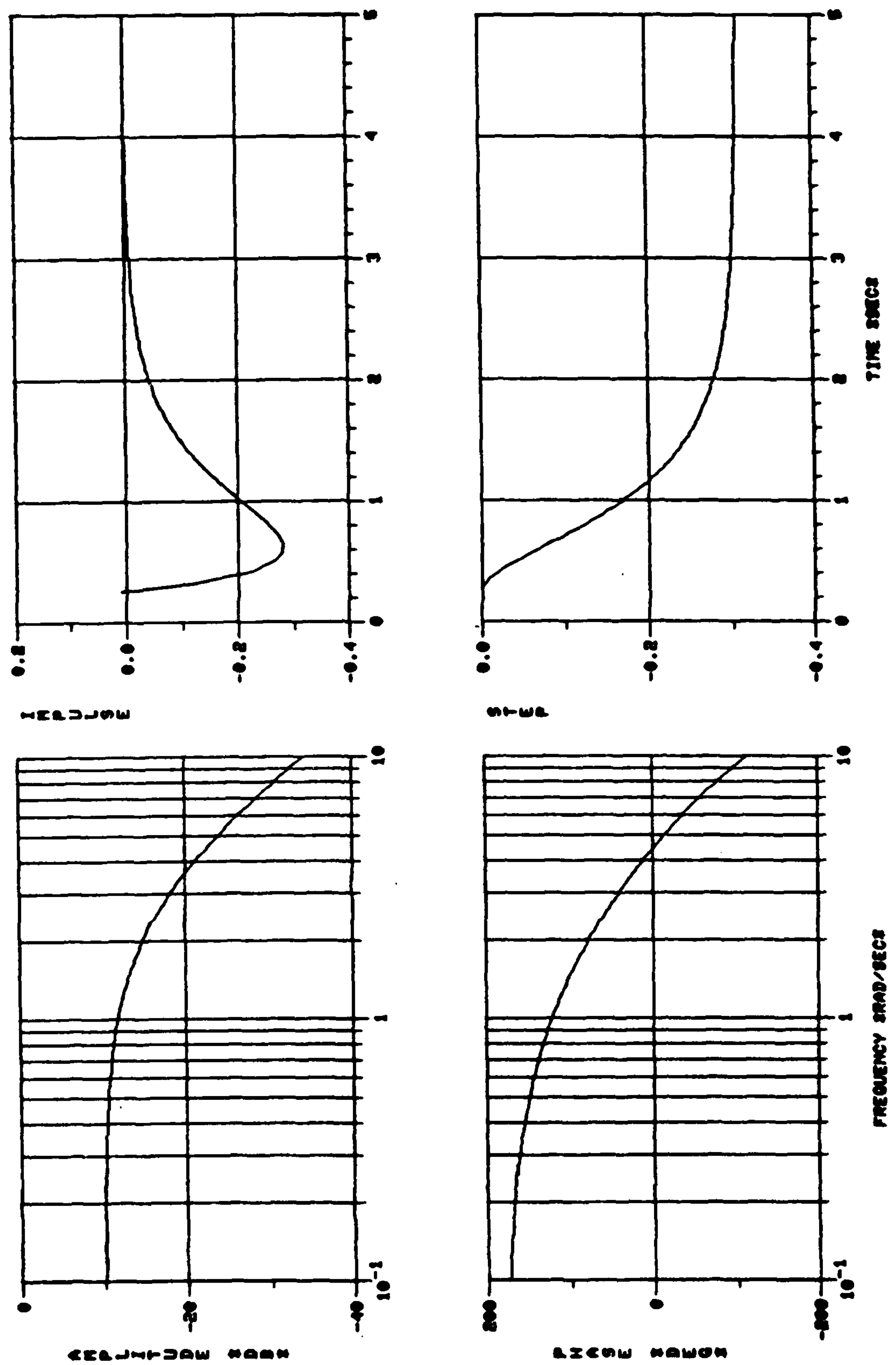
CASE 11 THETA/STK FORCE 10 LB STEP



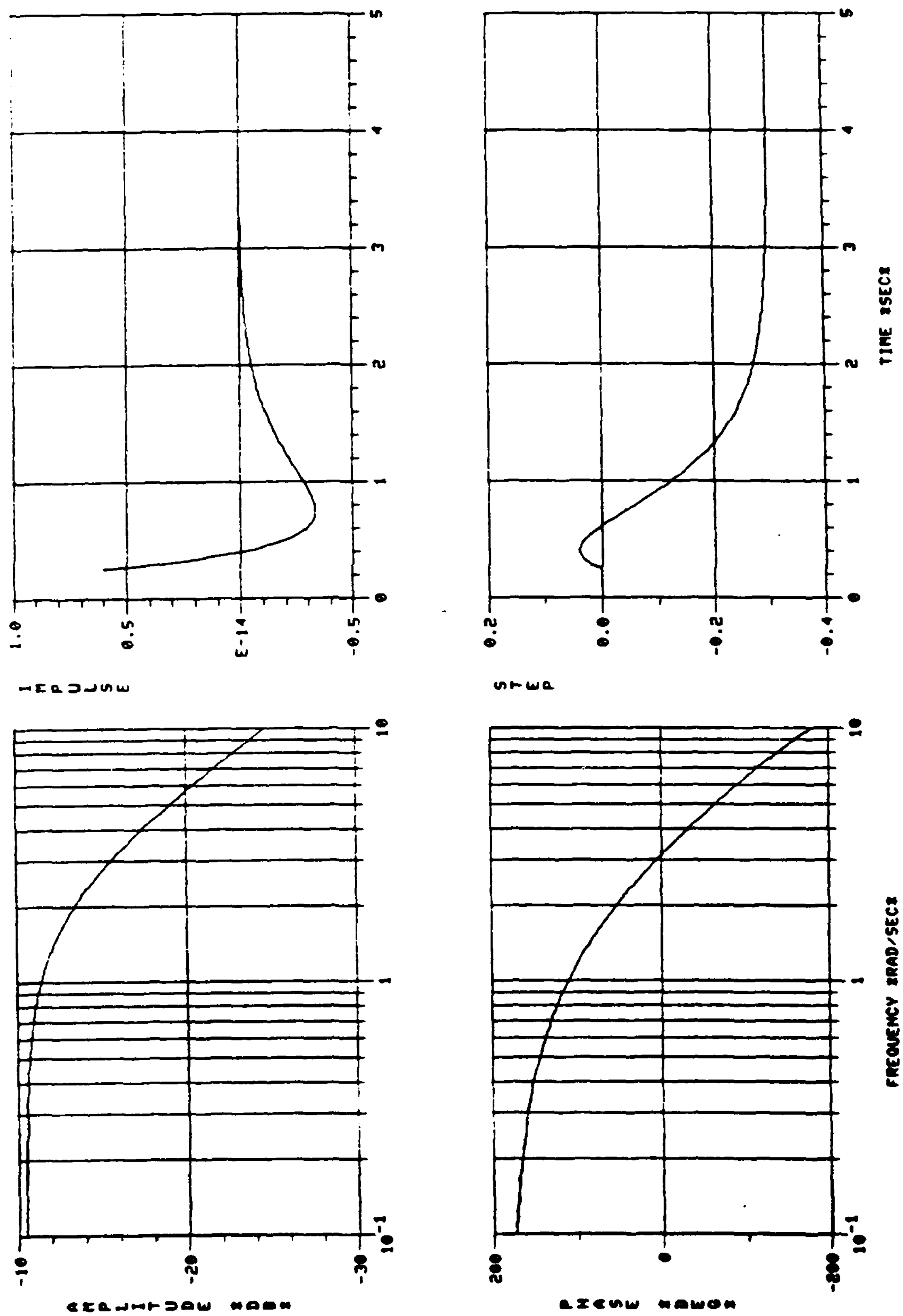
CASE 11 ALFA/STK FORCE 10 LB STEP

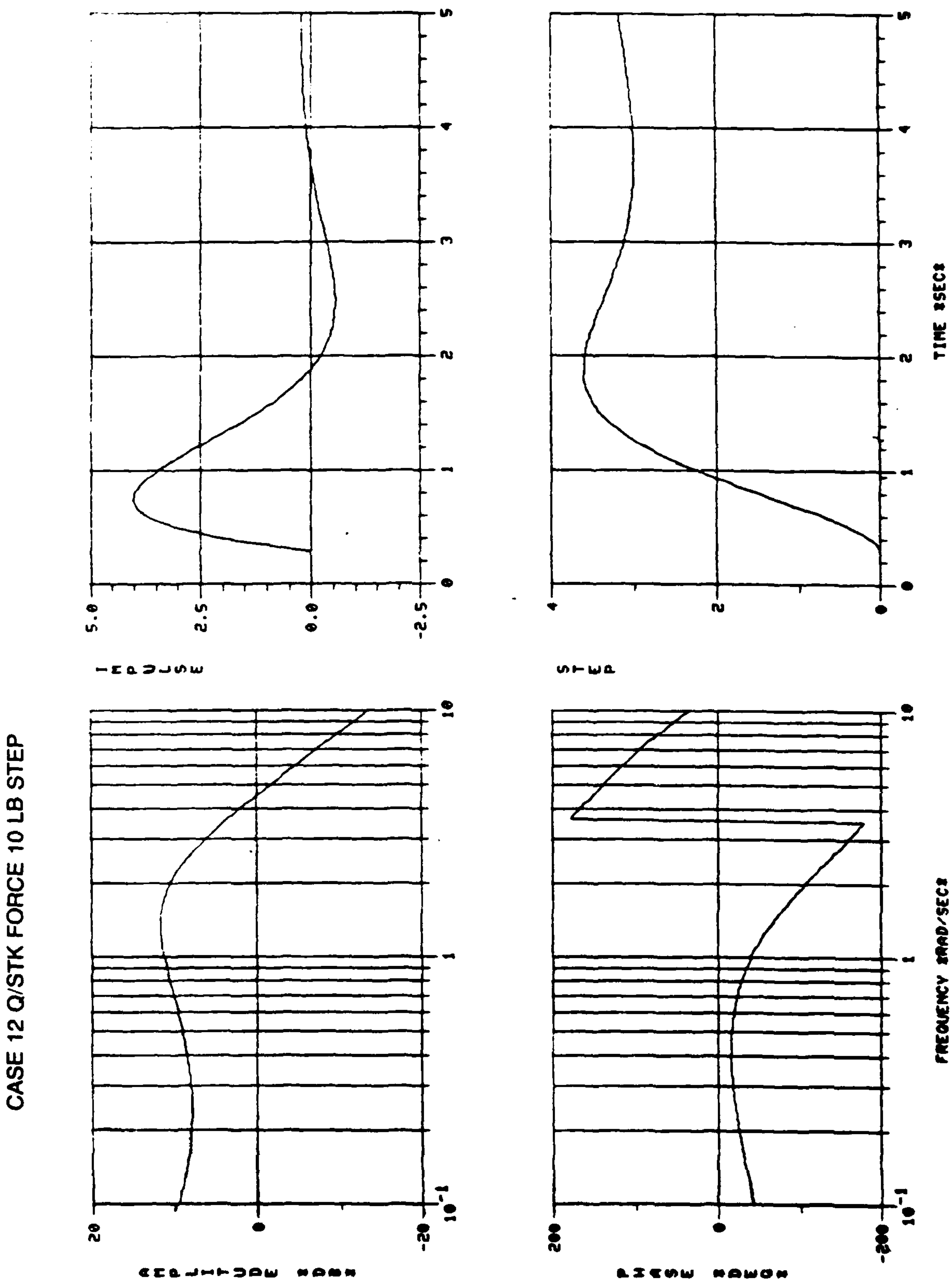


CASE 11 NZP/STK FORCE 10 LB STEP



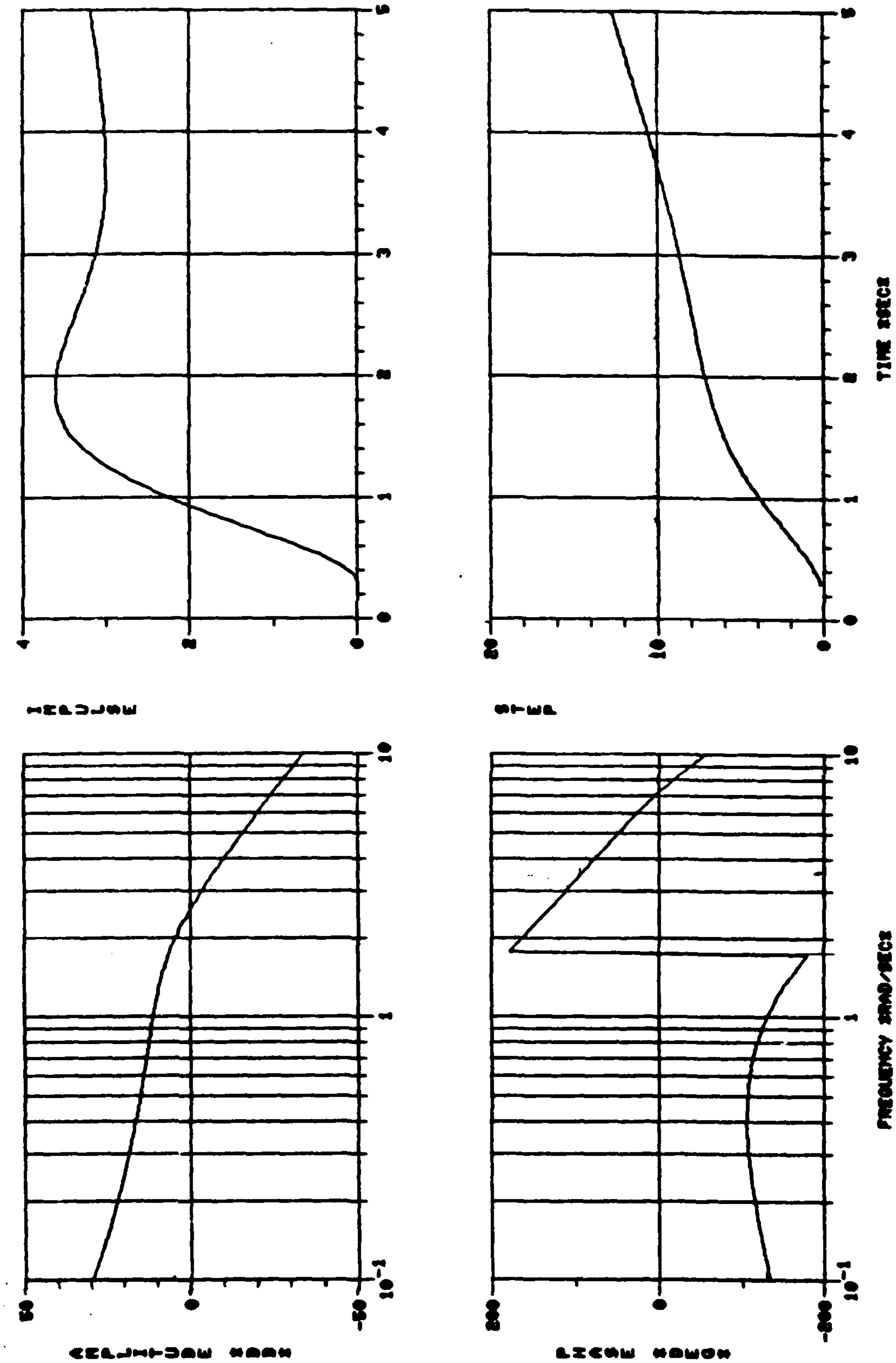
CASE 11 NZCG/STK FORCE 10 LB STEP



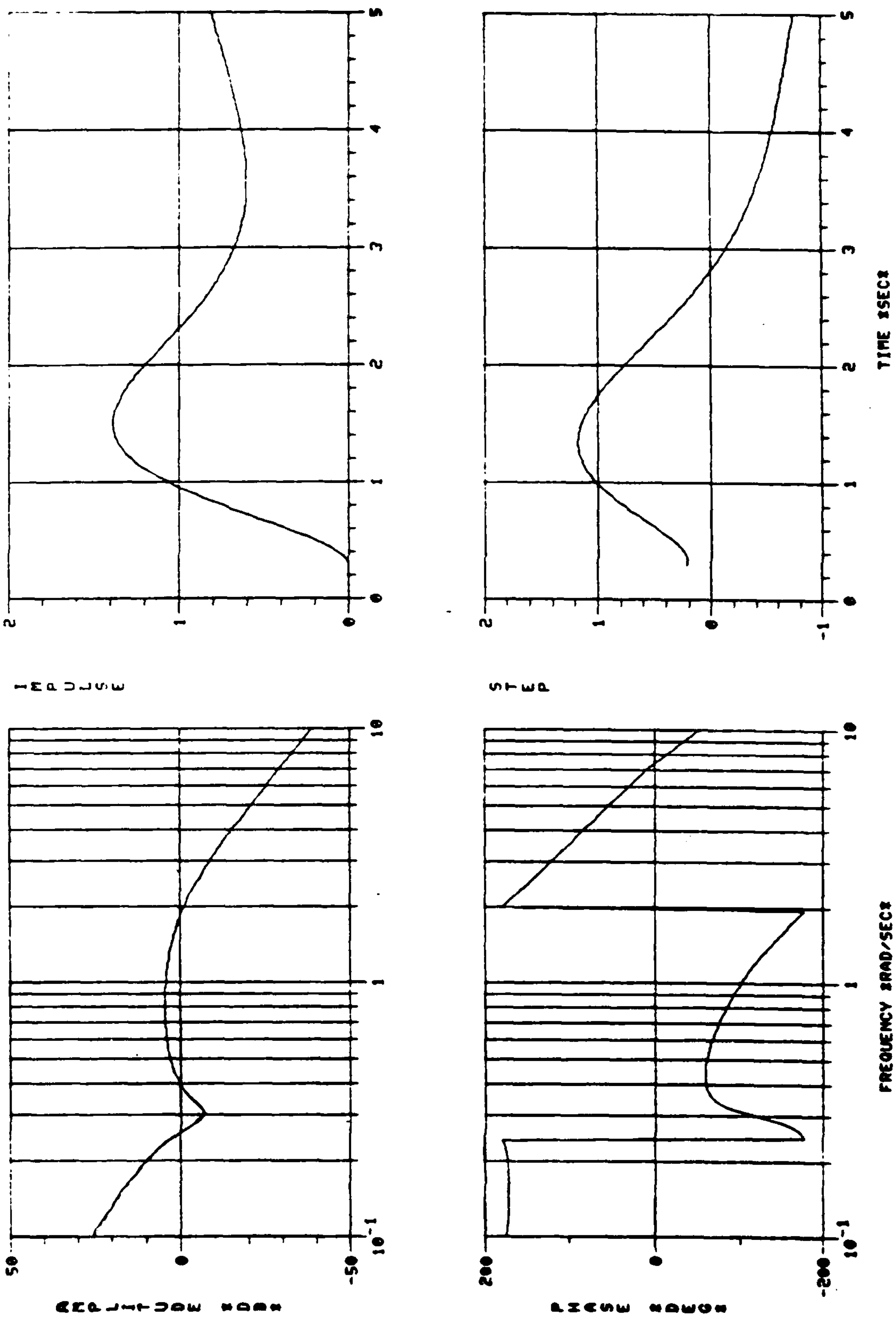


CASE 12 Q/STK FORCE 10 LB STEP

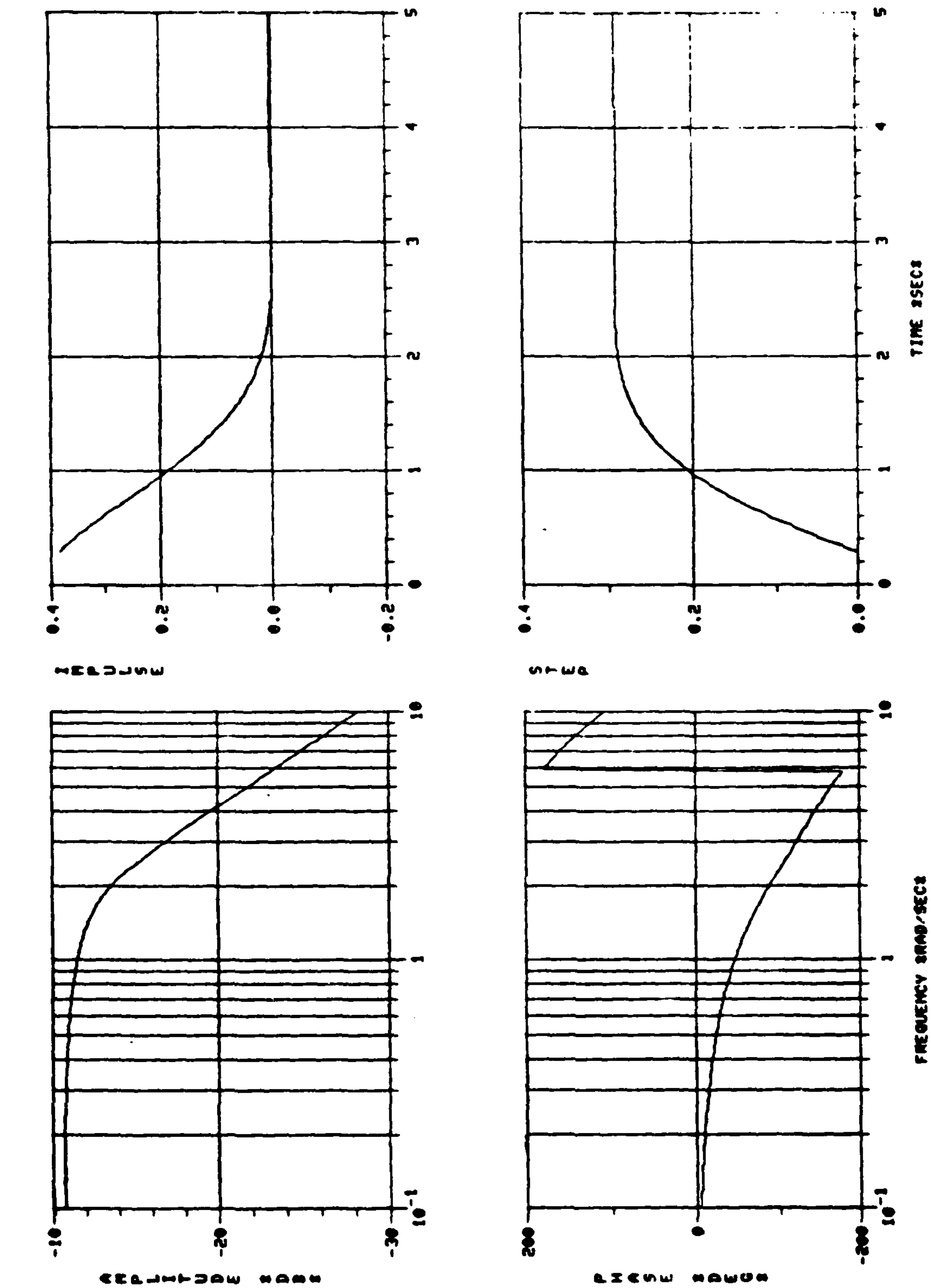
CASE 12 THETA/STK FORCE 10 LB STEP



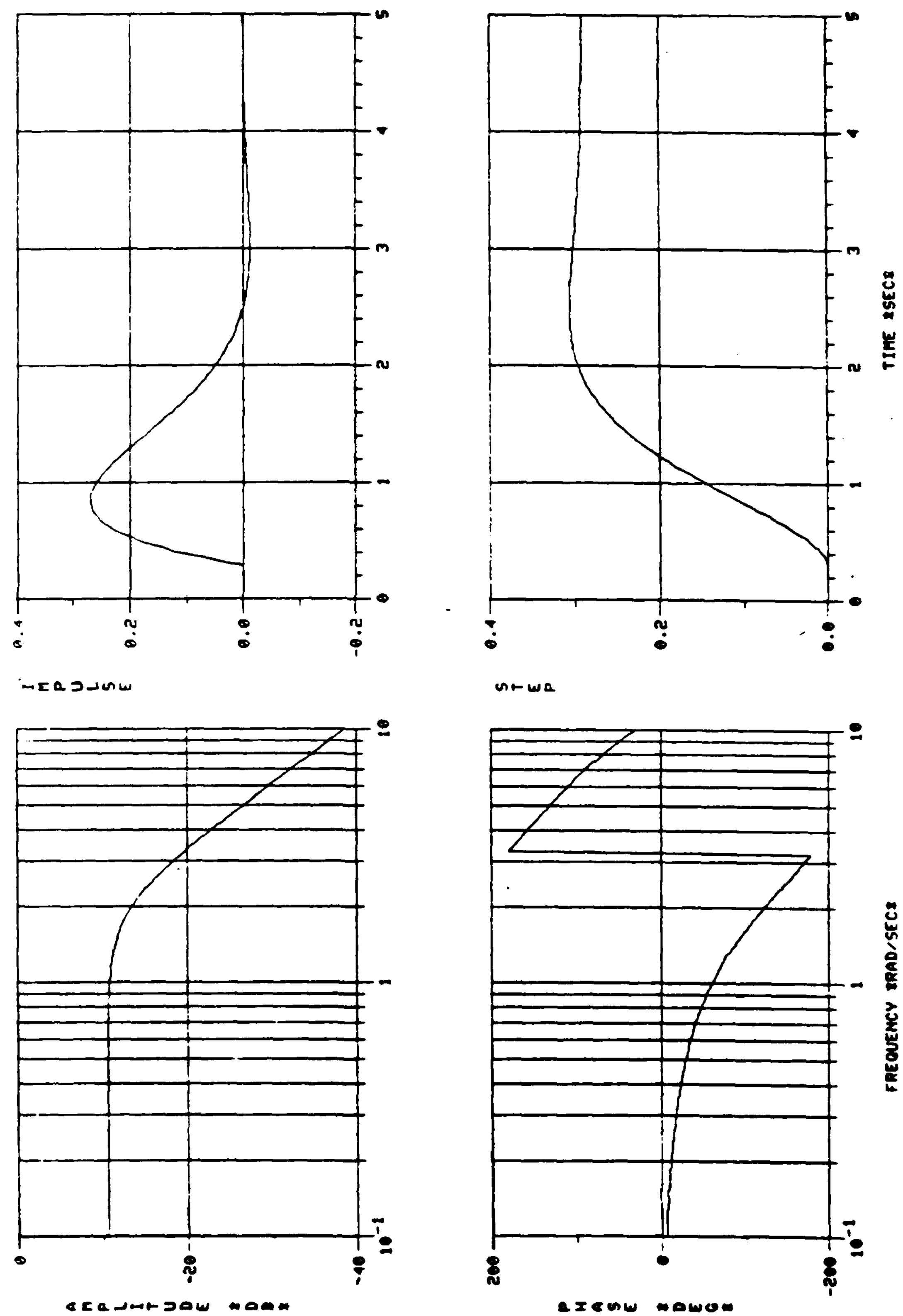
CASE 12 ALFA/STK FORCE 10 LB STEP



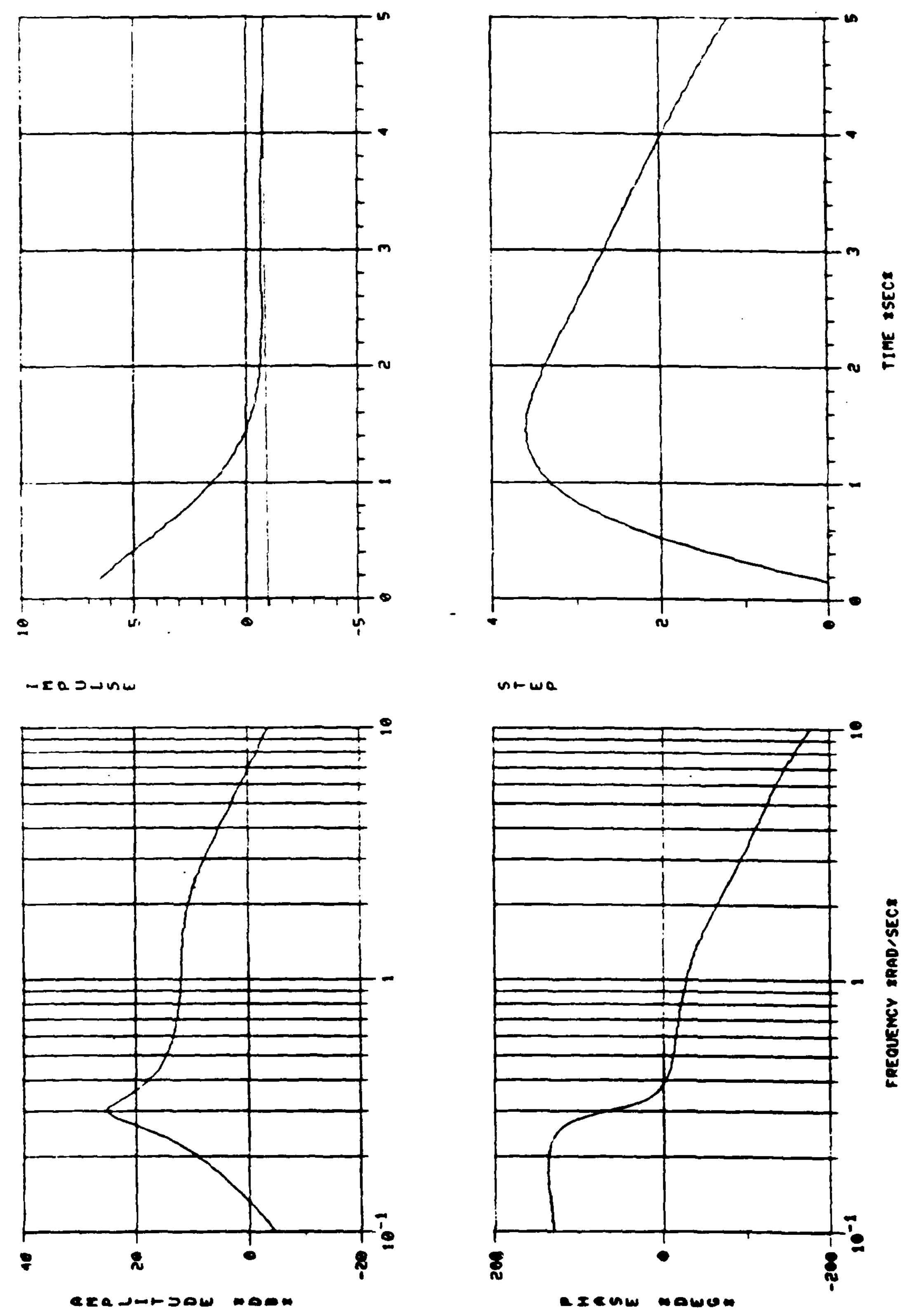
CASE 12 NZP/STK FORCE 10 LB STEP

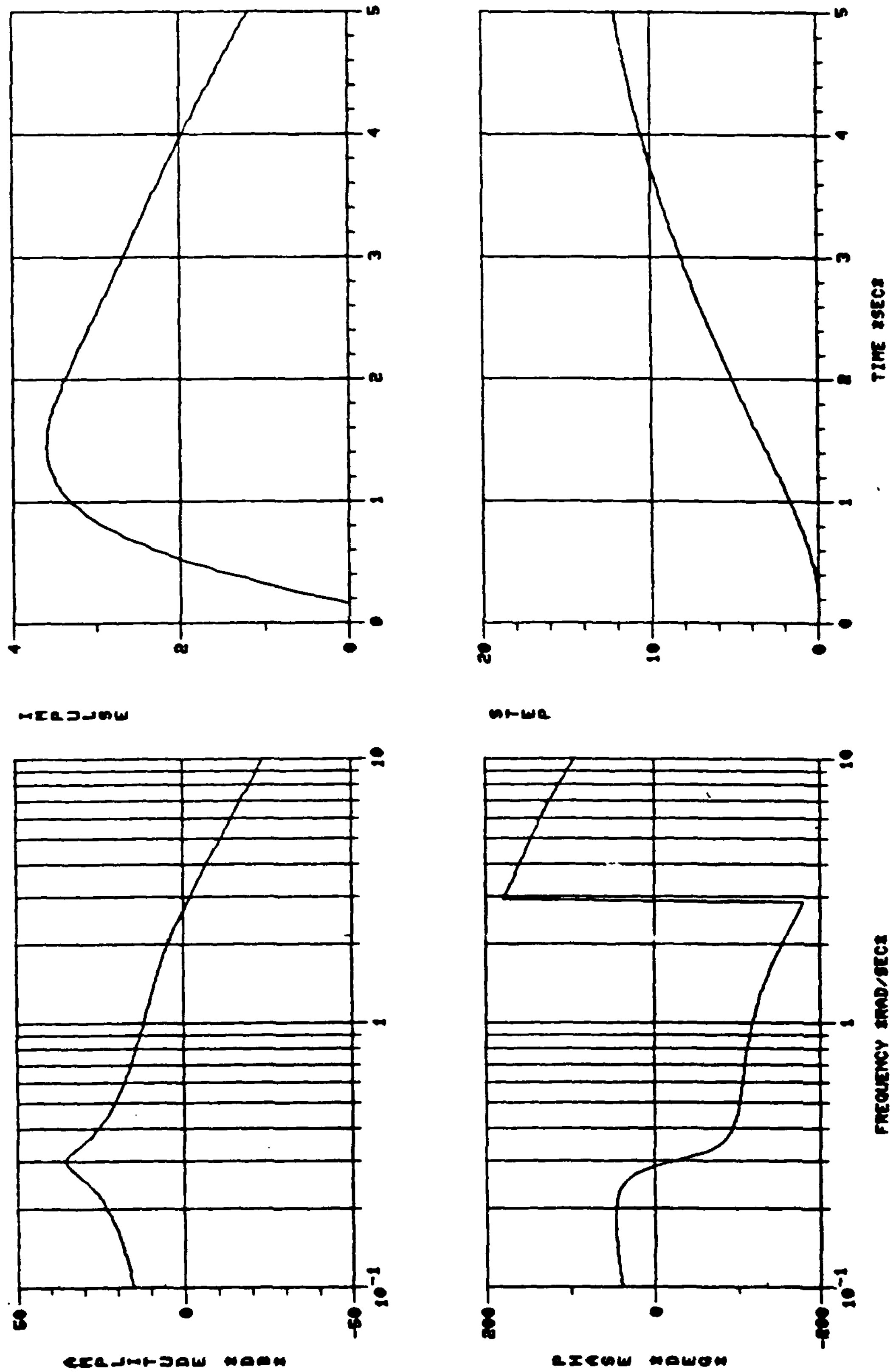


CASE 12 NZCG/STK FORCE 10 LB STEP



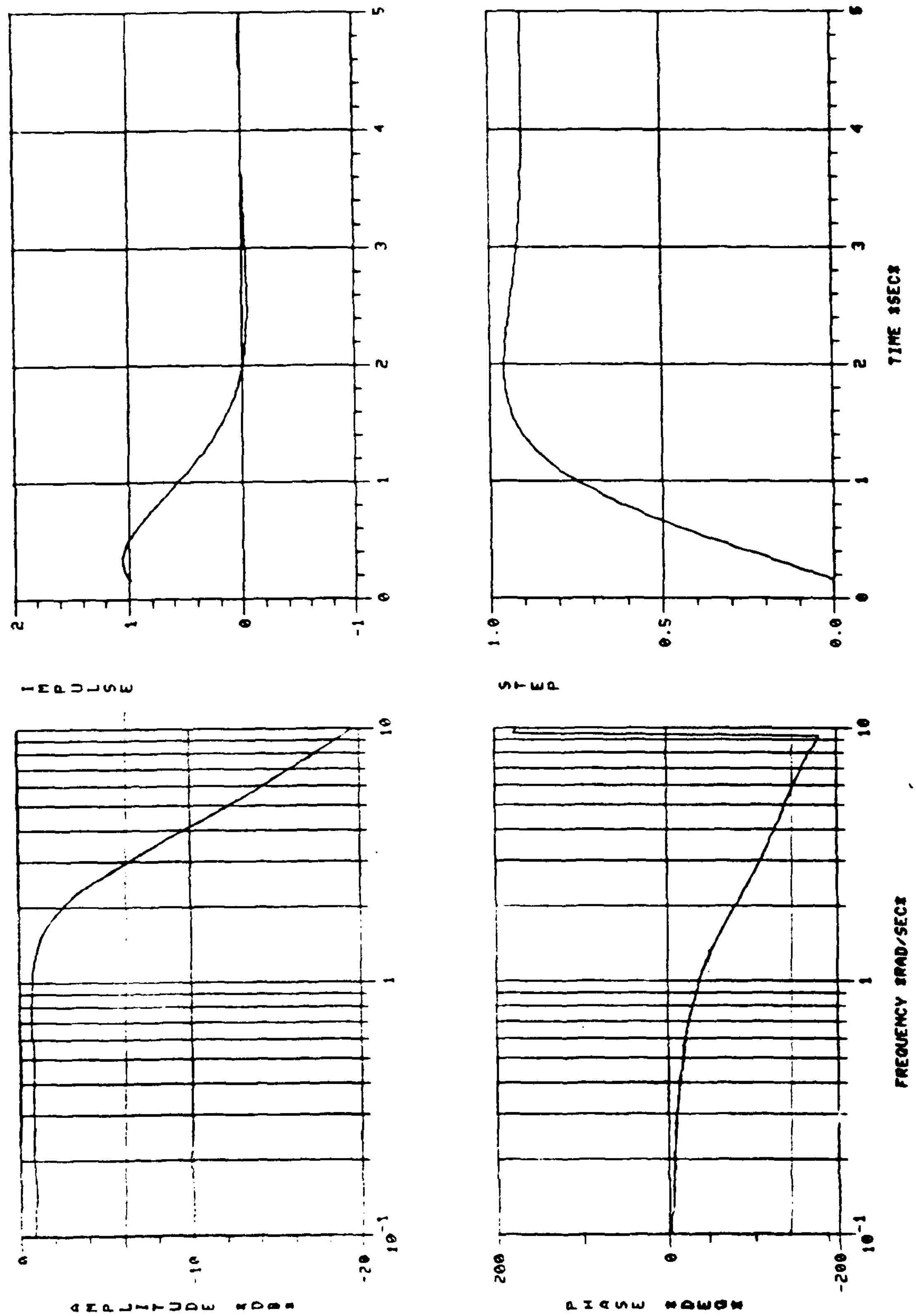
CASE 13 Q/STK FORCE 10 LB STEP



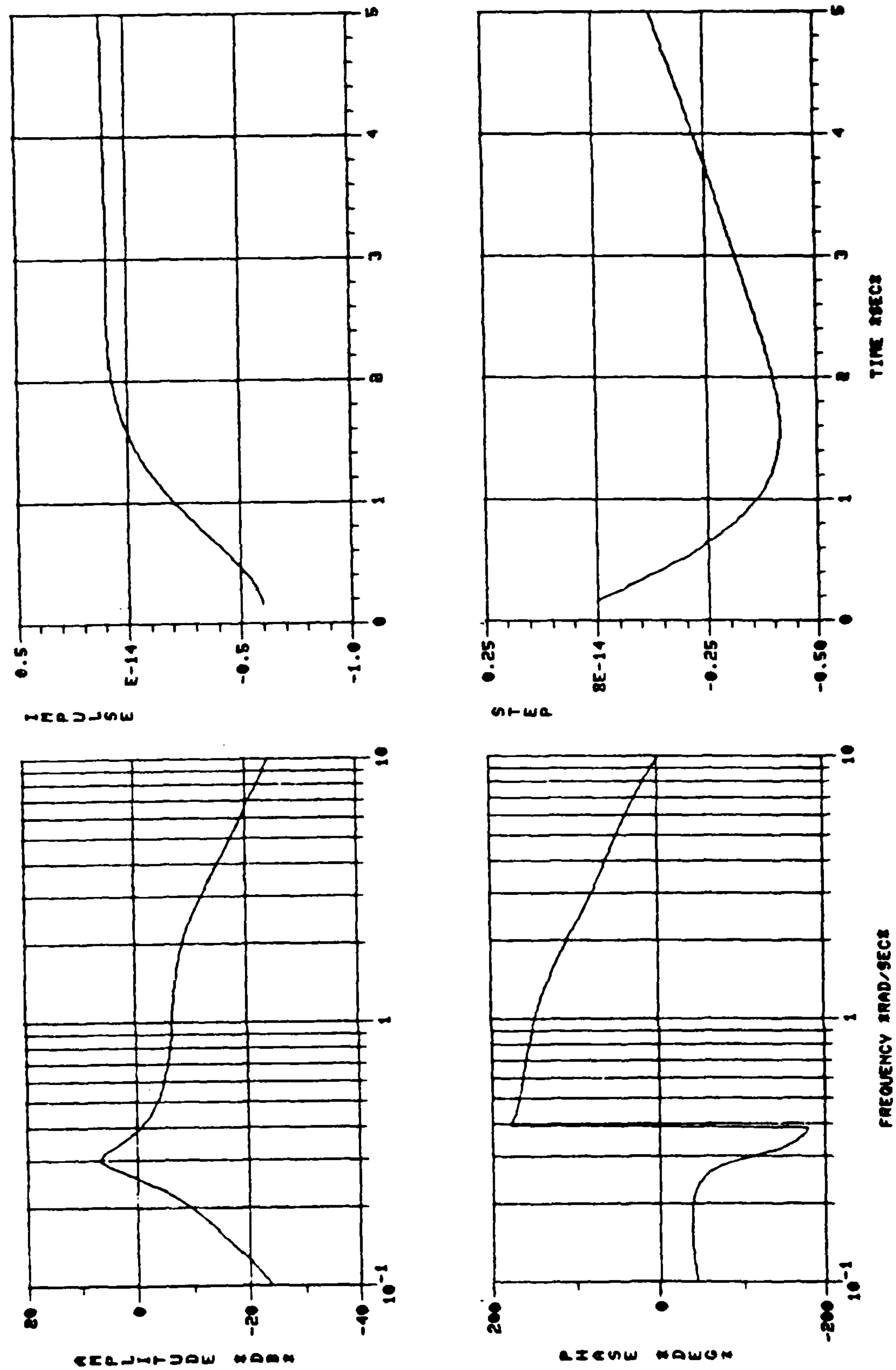


CASE 13 THETA/STK FORCE 10 LB STEP

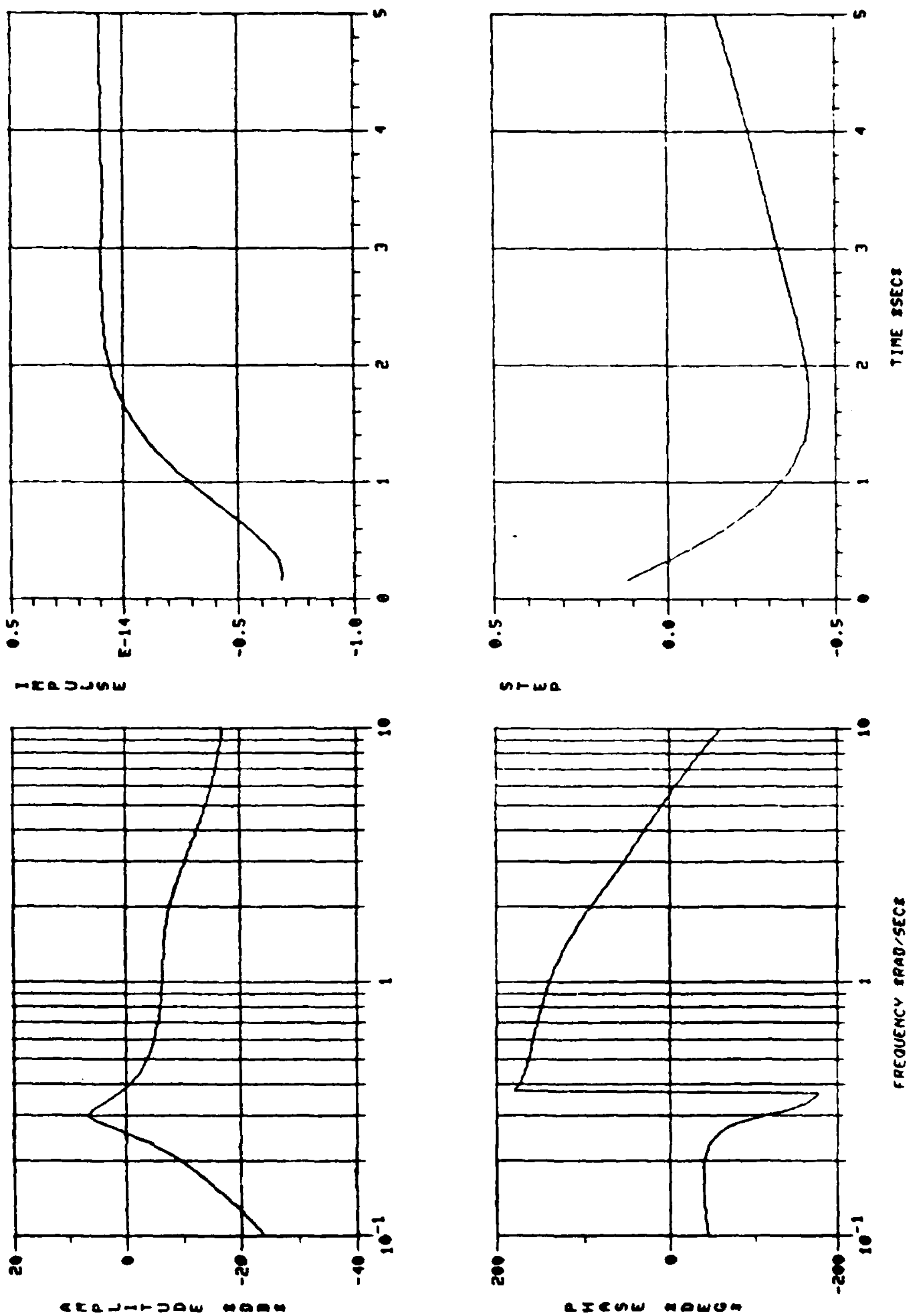
CASE 13 ALFA/STK FORCE 10 LB STEP



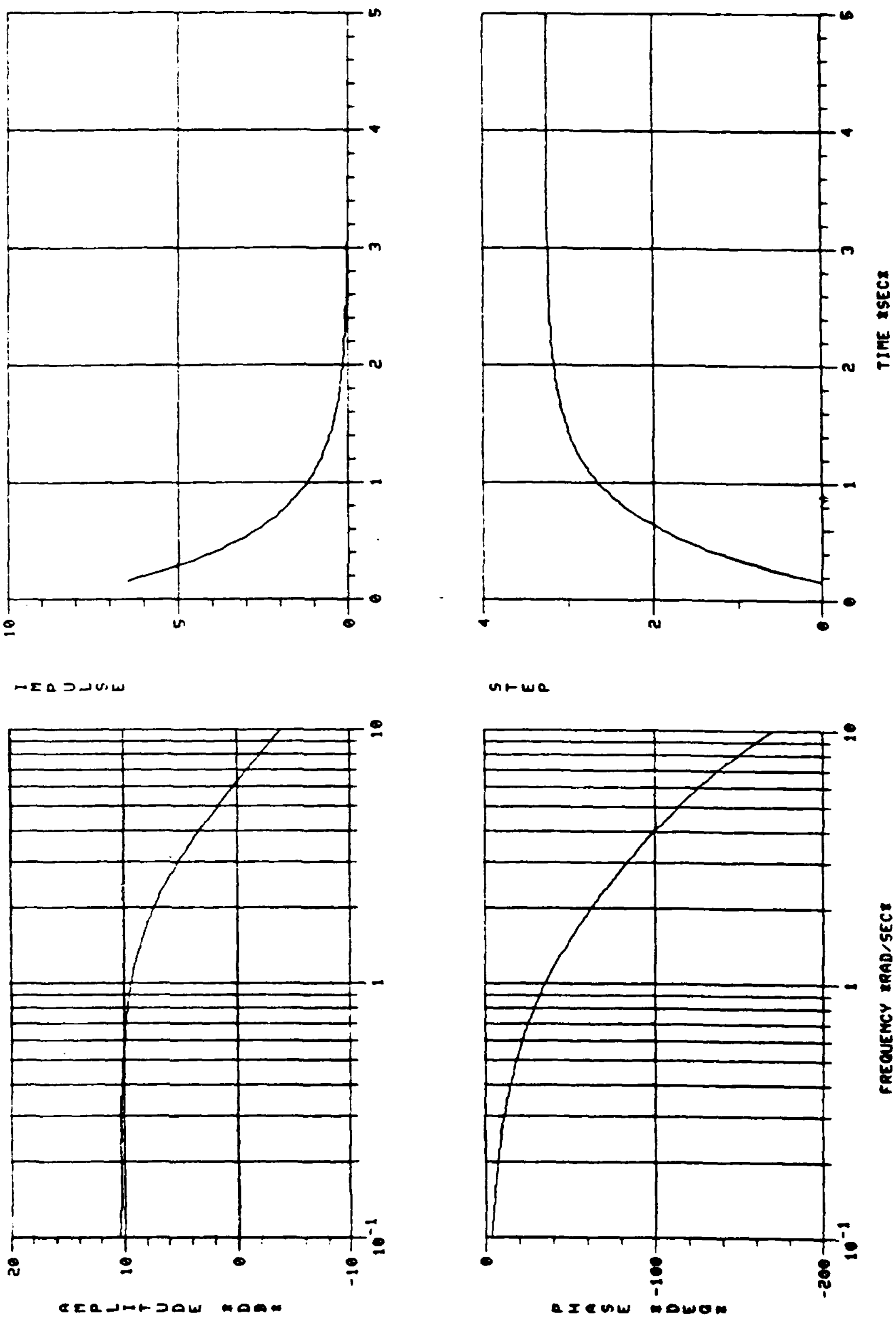
CASE 13 NZP/STK FORCE 10 LB STEP



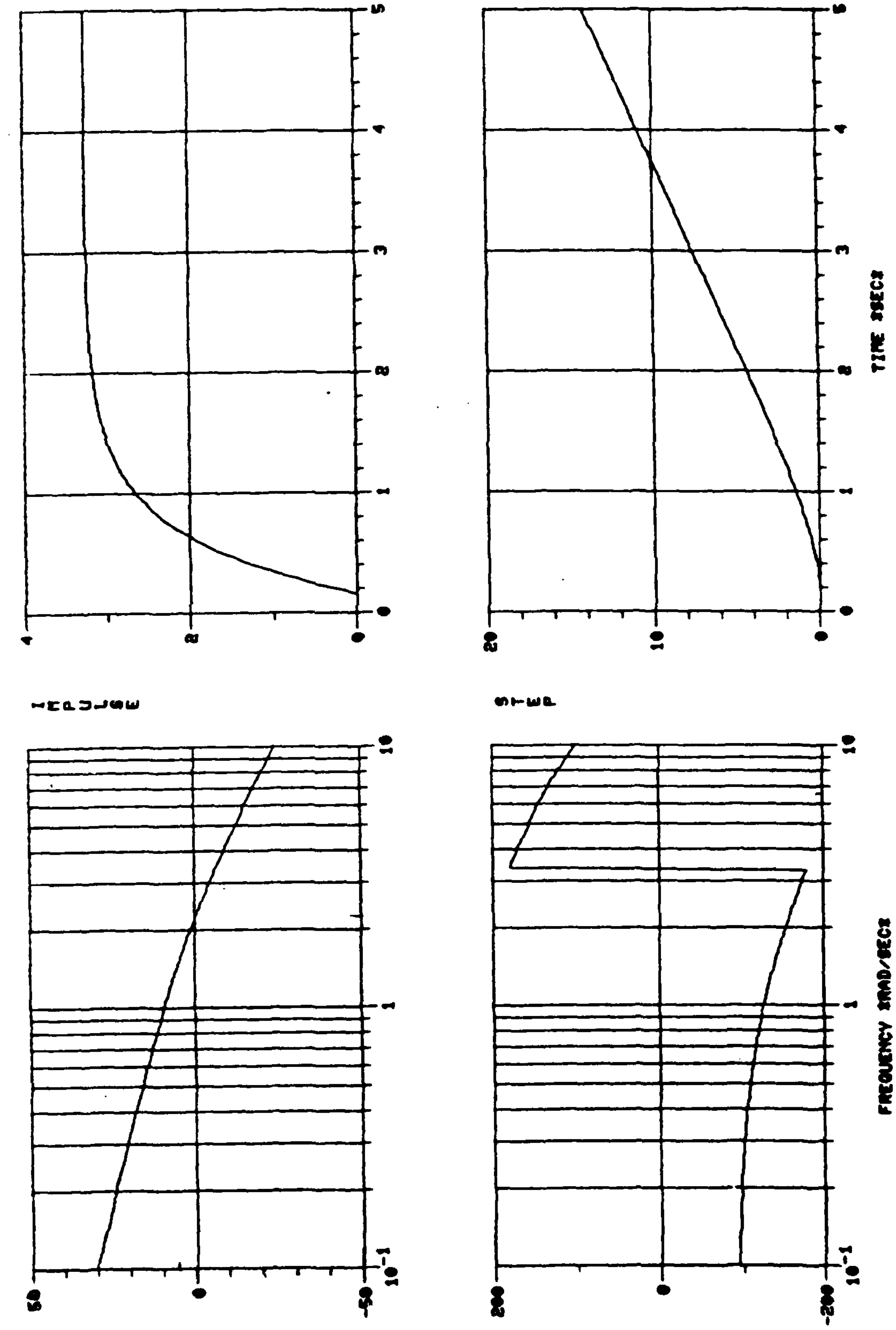
CASE 13 NZCG/STK FORCE 10 LB STEP



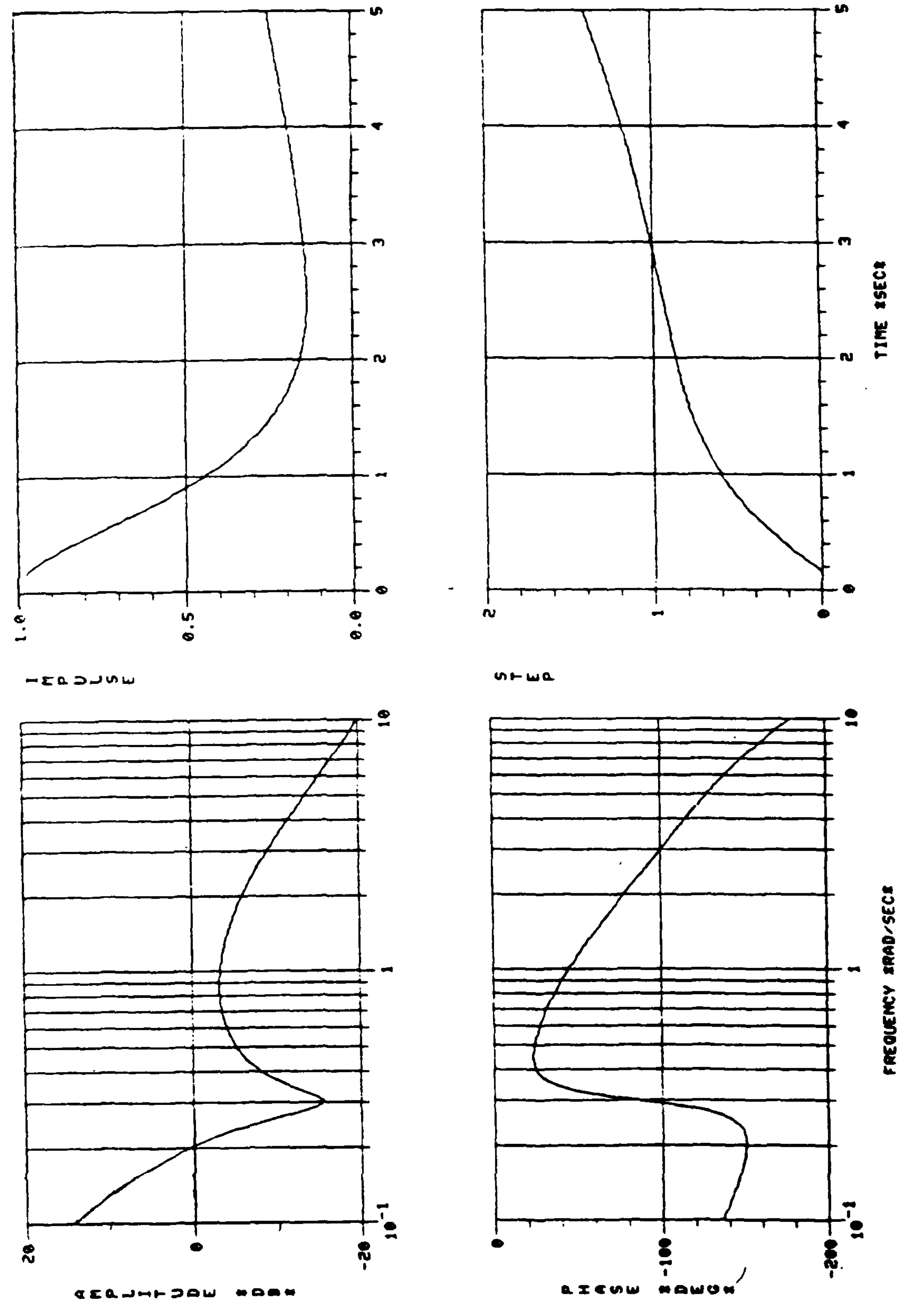
CASE 14 Q/STK FORCE 10 LB STEP

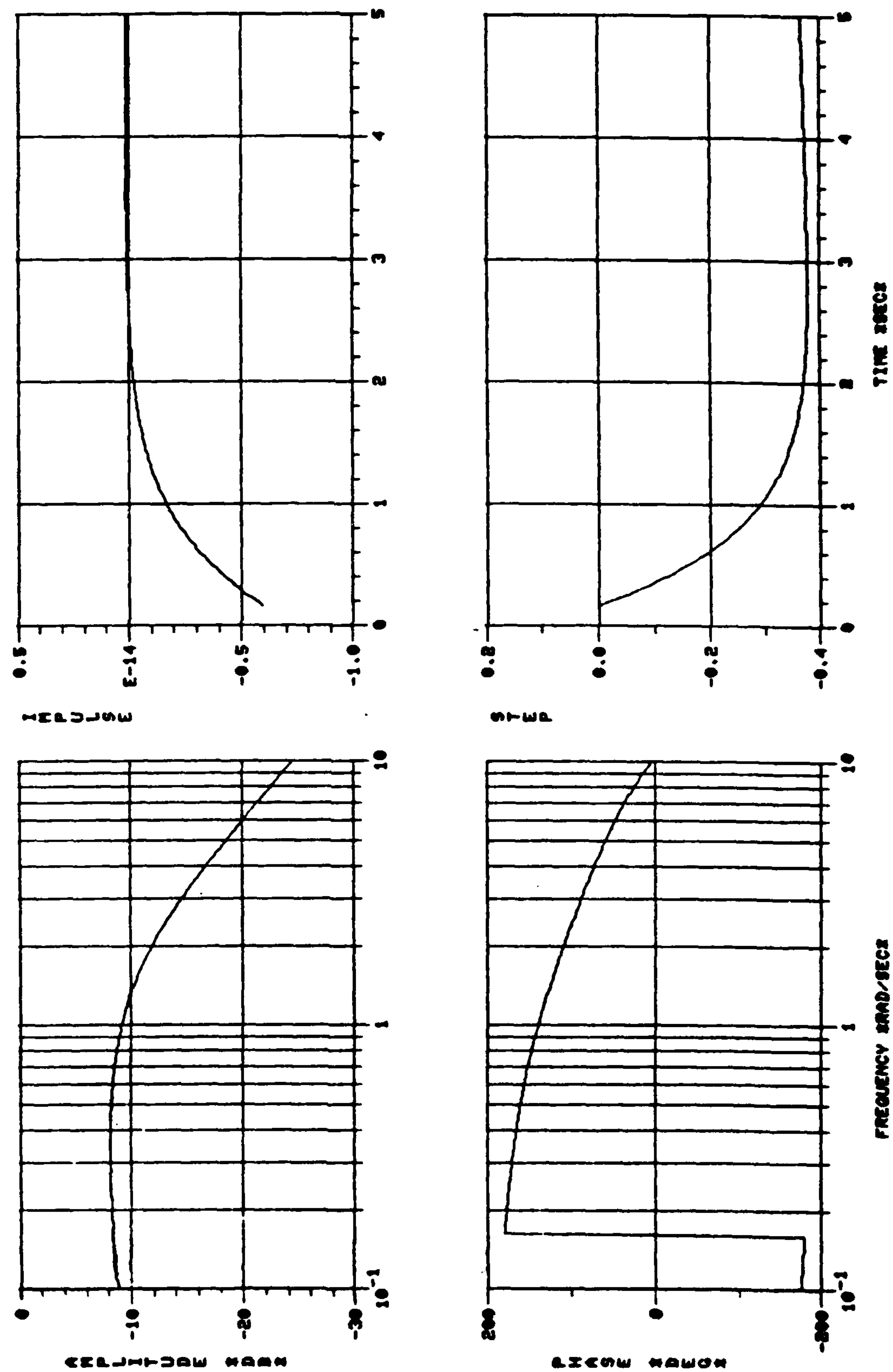


CASE 14 THETA/STK FORCE 10 LB STEP



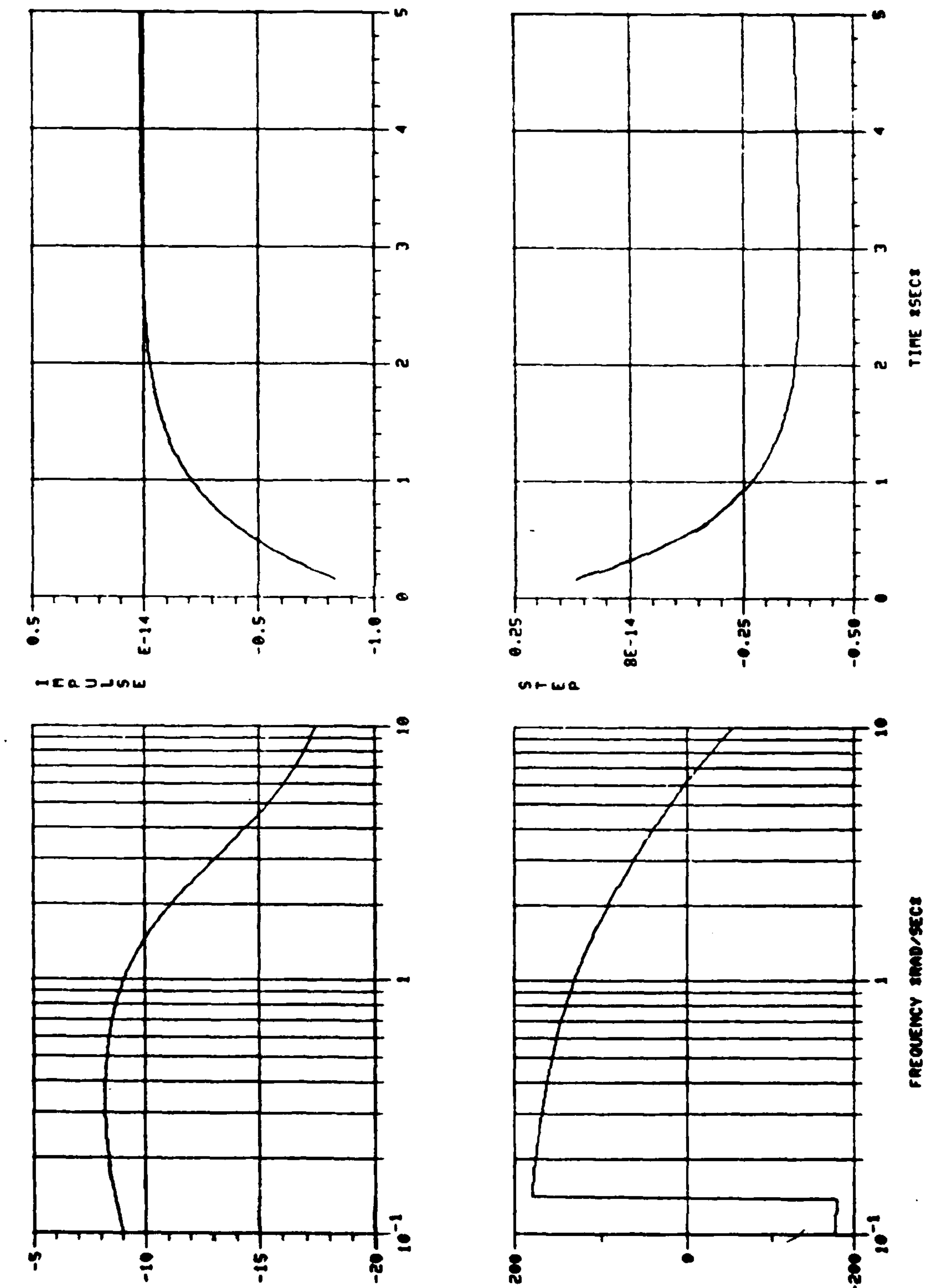
CASE 14 ALFA/STK FORCE 10 LB STEP



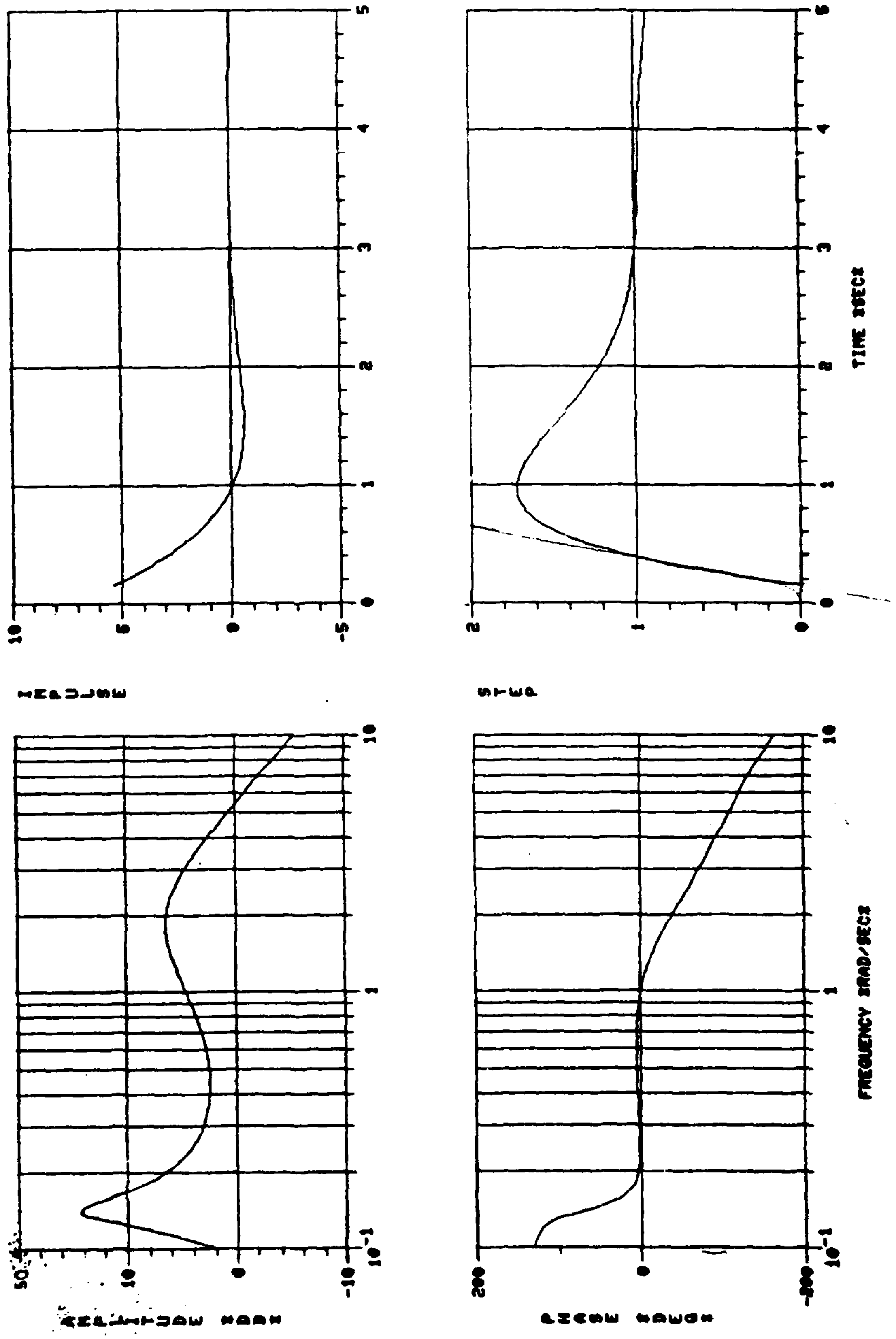


CASE 14 NZP/STK FORCE 10 LB STEP

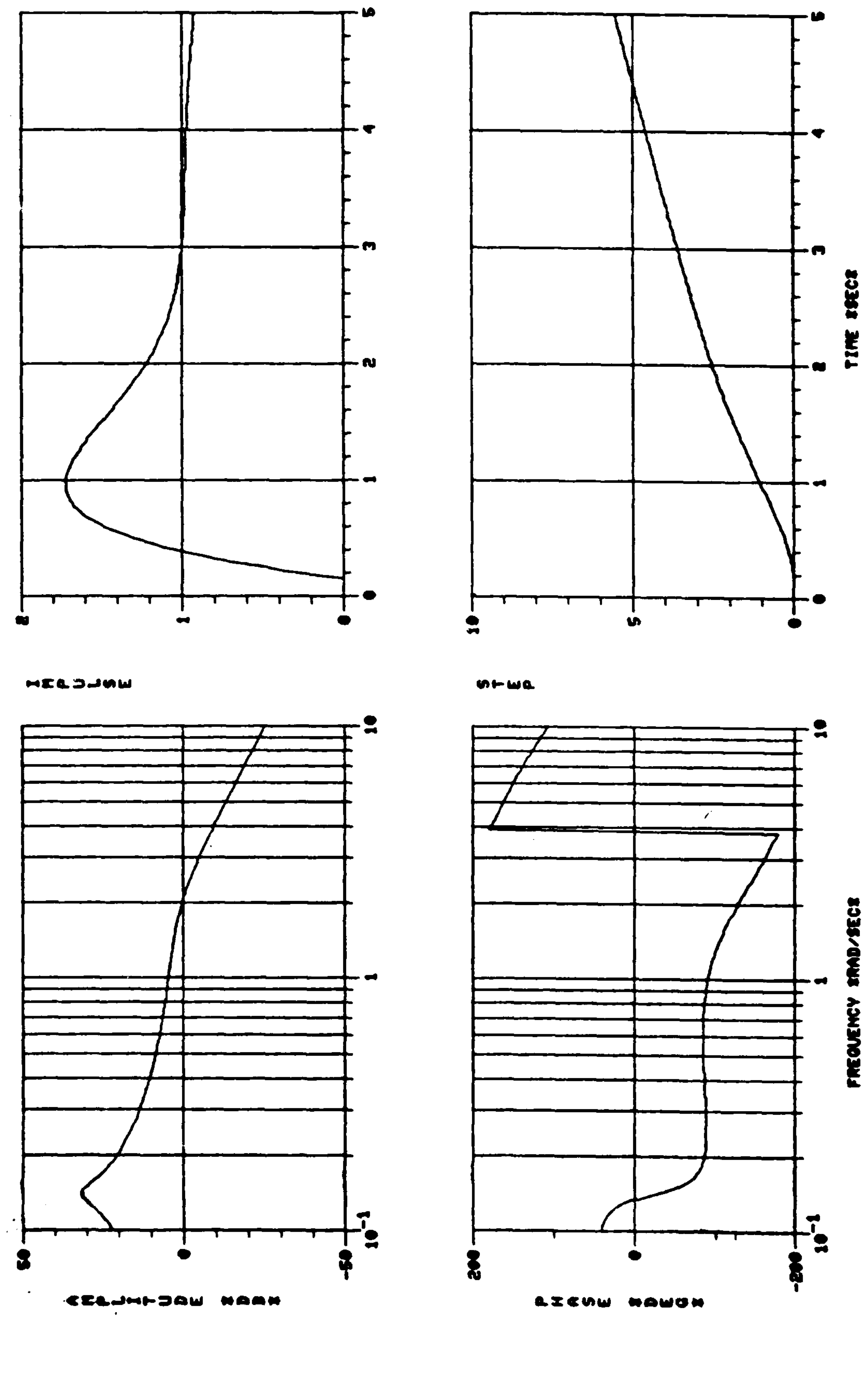
CASE 14 NZCG/STK FORCE 10 LB STEP



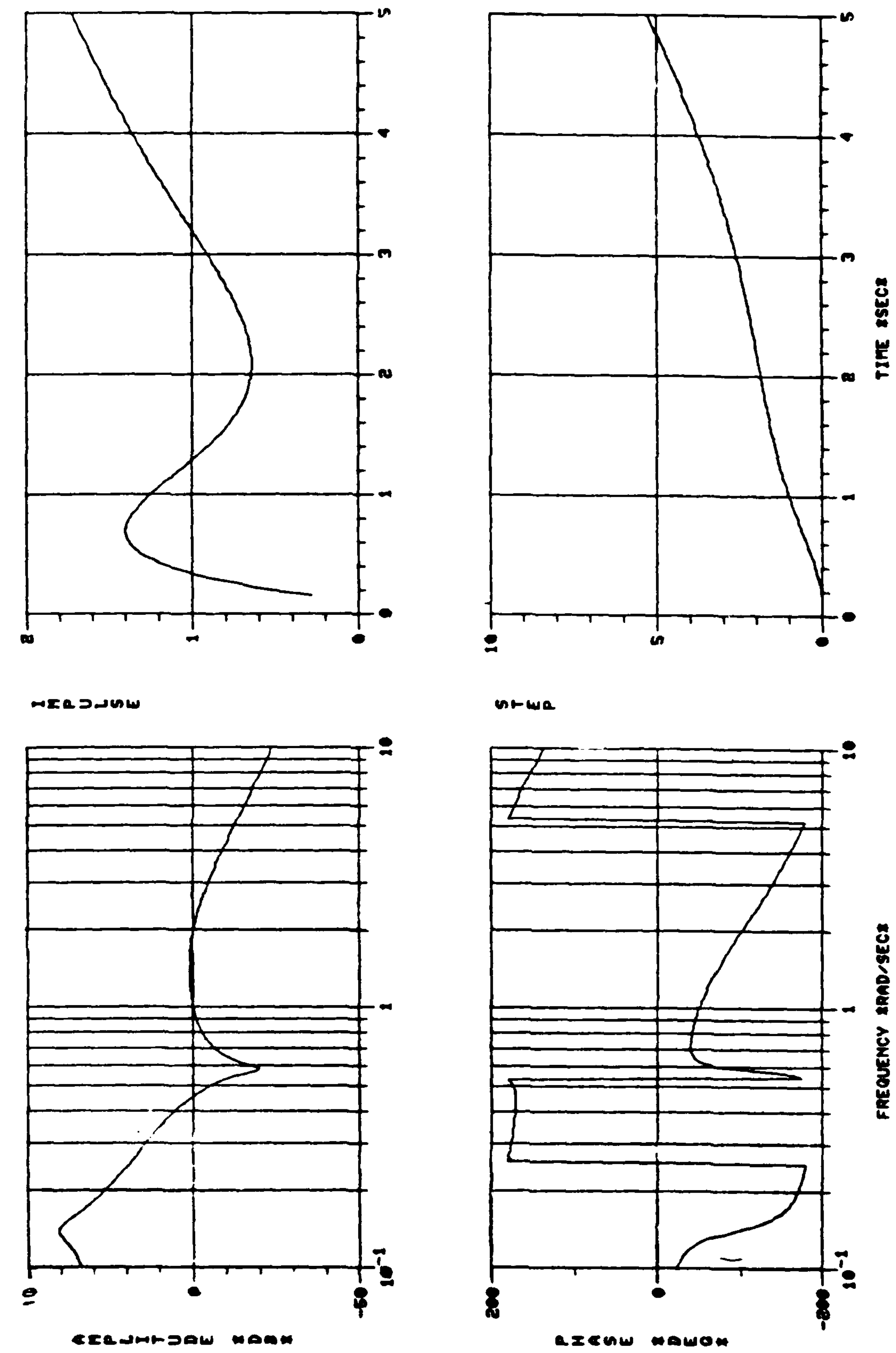
BASE CASE Q/STK FORCE 10 LB STEP



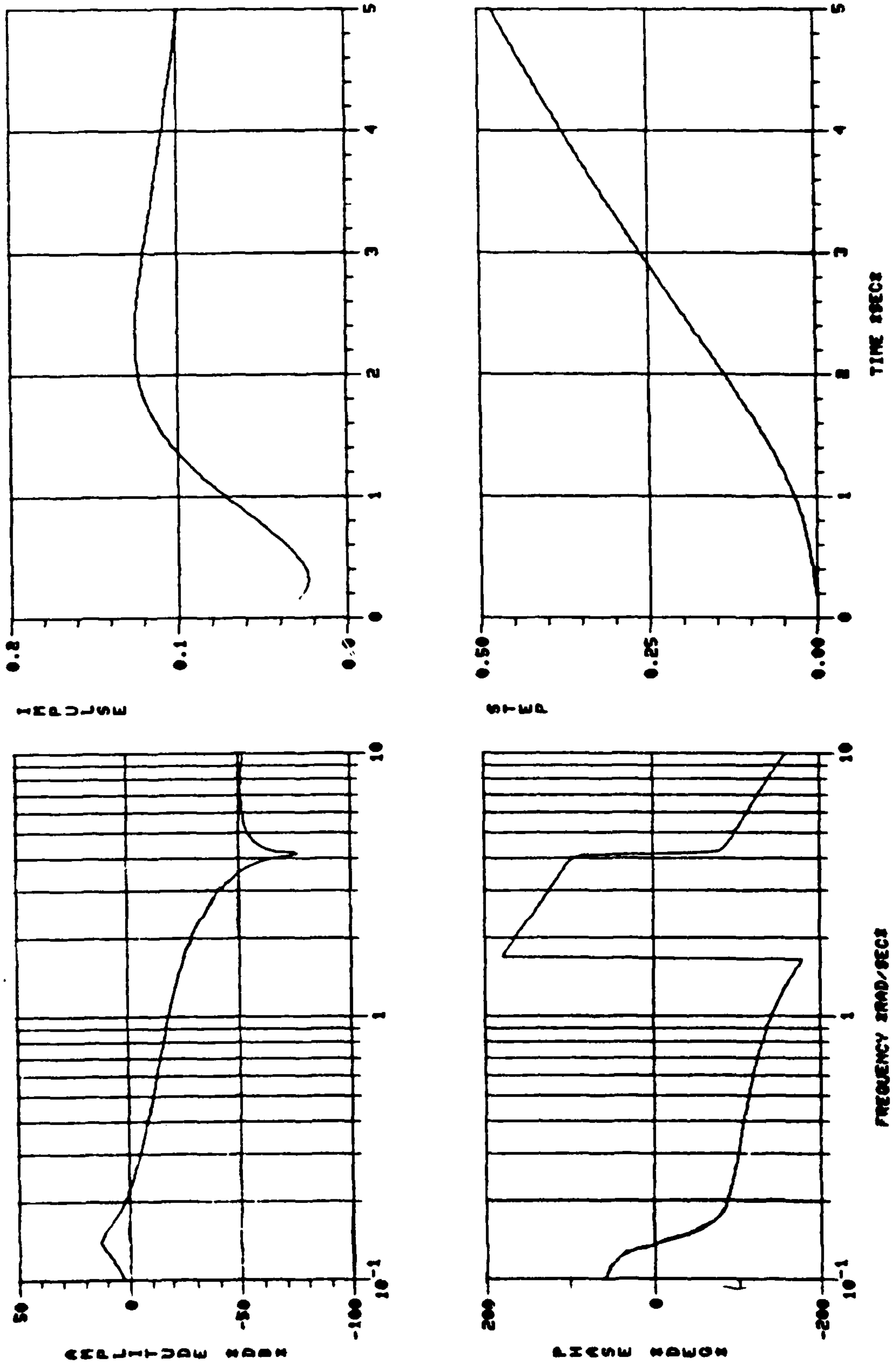
BASE CASE THETA/STK FORCE 10 LB STEP



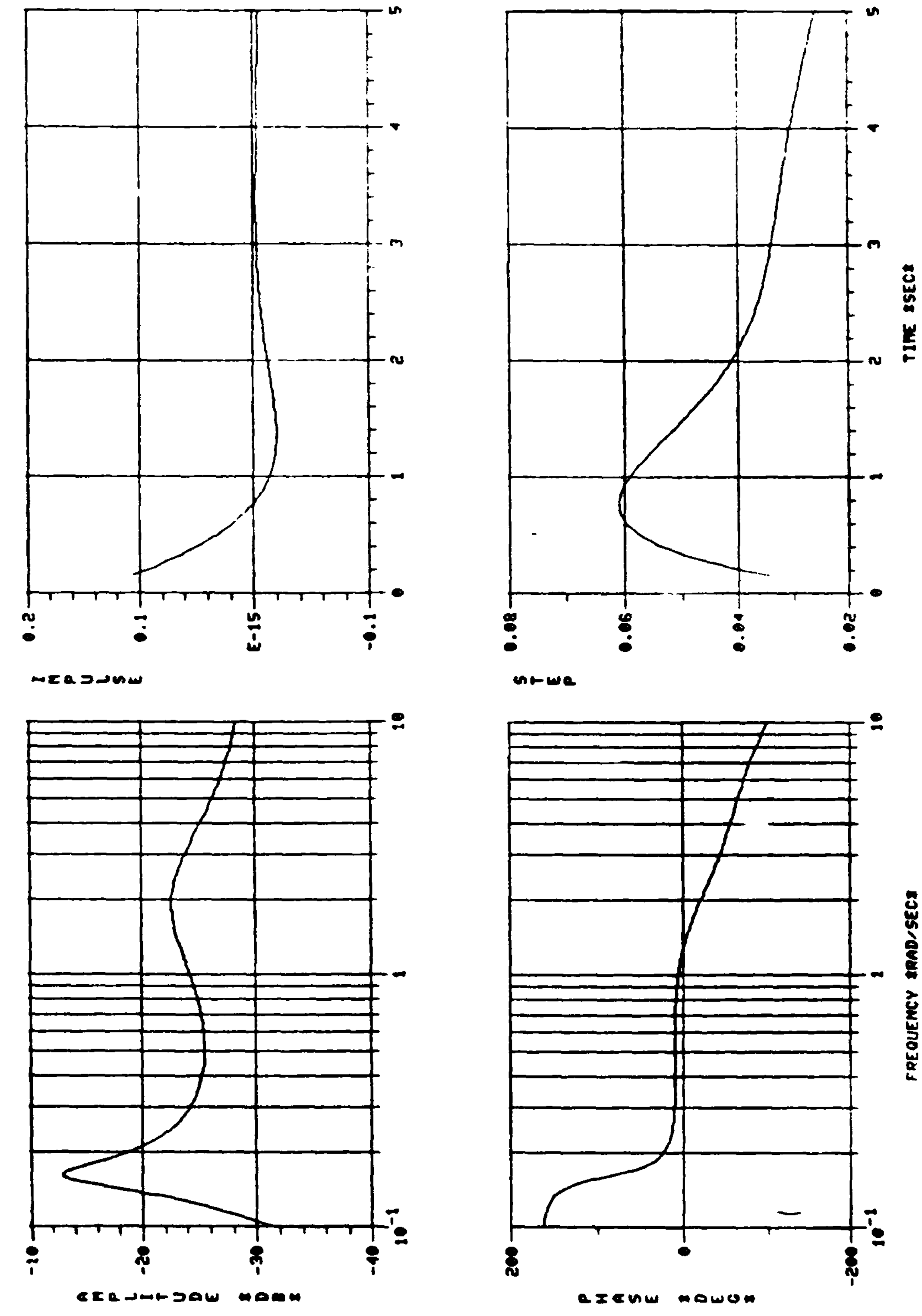
BASE CASE ALFA/STK FORCE 10 LB STEP



BASE CASE NZP/STK FORCE 10 LB STEP



BASE CASE NZCG/STK FORCE 10 LB STEP



APPENDIX B

This appendix presents the state space representation and corresponding transfer functions for each configuration used in this study. The state representation is in form of:

$$\dot{X} = FX + Gu$$

Where the state vector $X = \begin{bmatrix} q, \text{deg/sec} \\ \theta, \text{deg} \\ \alpha, \text{deg} \\ V, \text{ft/sec} \end{bmatrix}$

and the control vector $u = [\delta_e, \text{deg}]$

The F and G matrices are presented. In addition the command gain, Kc (deg/lb), is listed separately and should be multiplied by the gain of each numerator. The gain was chosen in the NASA/Calspan study to yield the same maximum $\dot{q}$ for each configuration to a 10 lb step input. Included in the gain term is the stick gradient (1 in/12 lb) so the transfer functions are with respect to the stick force input.

The transfer functions are written in shorthand notation where:

$$K\,(a)\,[\zeta, \omega] = K\,(s + a)\,(s^2 + 2\,\zeta\,\omega s + \omega^2)$$

The $n_{z_{cg}}$ and n_{z_p} transfer functions were determined from the α, q and θ transfer functions through the following relationships:

$$n_{z_{cg}} = \frac{a_z}{g} = \frac{U_o\, s\, \alpha}{57.3\, g} - \frac{U_o\, s\, \theta}{57.3\, g}$$

and $$n_{z_p} = n_{z_{cg}} - \frac{\dot{q}\, Xmp}{57.3\, g}$$

where U_o = 225 ft/sec and Xmp = 33.8 ft

Configuration 1 α-cmd, $\omega_{sp} = 2,\ 1/\tau_{\theta_2} = .5$

$$F = \begin{bmatrix} -1.4047 & -.1536 & -5.7022 & .0896 \\ 1.0000 & .0000 & .0000 & .0000 \\ .3528 & .0165 & -1.4520 & -.0237 \\ -.1440 & -1.3427 & 1.2930 & -.0033 \end{bmatrix} \qquad G = \begin{bmatrix} -1.0000 \\ .0000 \\ -.1500 \\ .0000 \end{bmatrix}$$

$K_c = -.65$

$N_q = -1\ (0)\ (.1)\ (.5)$

$N_\theta = -1\ (.1)\ (.5)$

$N_\alpha = -.15\ (3.7)\ [.1, .3]$

$N_{n_{z_{cg}}} = -.018\ (0)\ (0)\ (.955)\ (-3.862)$

$N_{n_{z_p}} = -.0003\ (0)\ (0)\ (1.063)\ (-214.4)$

$D = [.7, 2]\ [.1, .3]$

Time Delay = .16 sec

Configuration 2 q-cmd, $\omega_{sp} = 2,\ 1/\tau_{\theta_2} = .5$

$$F = \begin{bmatrix} -8.0000 & .0000 & .0000 & .0000 \\ 1.0000 & .0000 & .0000 & .0000 \\ -.6365 & .0396 & -.5967 & -.0371 \\ -.1440 & -1.3427 & 1.2930 & -.0033 \end{bmatrix} \qquad G = \begin{bmatrix} -1.0000 \\ .0000 \\ -.1500 \\ .0000 \end{bmatrix}$$

$K_c = -.975$

$Nq = -1\ (0)\ (.5)$

$N_\theta = -1\ (.5)$

$N_\alpha = -.15\ (3.7)\ [.1,\ .3]$

$Nn_{z_{cg}} = -.018\ (0)\ (0)\ (.955)\ (-3.862)$

$Nn_{z_p} = -.0003\ (1.063)\ (-214.4)$

$D = (0)\ (.1)\ (.5)\ (8)$

Time Delay = .15 sec

Configuration 3 Short term αcmd/long term q-cmd, $\omega_{sp} = 2,\ 1/\tau_{\theta_2} = .5$

$$F = \begin{bmatrix} -1.5868 & -.5784 & -4.7550 & -.3556 \\ 1.0000 & .0000 & .0000 & .0000 \\ .3255 & -.0472 & -1.3099 & -.0905 \\ -.1440 & -1.3427 & 1.2930 & -.0033 \end{bmatrix} \qquad G = \begin{bmatrix} -1.0000 \\ .0000 \\ -.1500 \\ .0000 \end{bmatrix}$$

$K_c = -.65$

$Nq = -1\ (0)\ (.1)\ (.5)$

$N_\theta = -1\ (.1)\ (.5)$

$N_\alpha = -.15\ (3.7)\ [.1,\ .3]$

$Nn_{z_{cg}} = .018\ (0)\ (0)\ (.955)\ (-3.862)$

$N_{z_p} = .0003\ (0)\ (0)\ (1.064)\ (-214.4)$

$D = (0)\ (.1)\ [.7,\ 2]$

Time Delay = .16 sec

Configuration 4 Short term q-cmd/long term α-cmd, $\omega_{sp} = 2$, $1/\tau_{\theta_2} = .5$

$$F = \begin{bmatrix} -8.1720 & -.4709 & 1.4131 & .5428 \\ 1.0000 & .0000 & .0000 & .0000 \\ -.6623 & -.0311 & -.3847 & .0443 \\ -.1440 & -1.3427 & 1.2930 & -.0033 \end{bmatrix} \qquad G = \begin{bmatrix} -1.0000 \\ .0000 \\ -.1500 \\ .0000 \end{bmatrix}$$

$K_c = -.975$

$Nq = -1\ (0)\ (.1)\ (.5)$

$N_\theta = -1\ (.1)\ (.5)$

$N_\alpha = -.15\ (3.7)\ [.1, .3]$

$Nn_{z_{cg}} = -.018\ (0)\ (0)\ (.955)\ (-3.862)$

$Nn_{z_p} = -.0003\ (0)\ (0)\ (1.063)\ (-214.4)$

$D = (.5)\ (8)\ [.1, .3]$

Time Delay = .14 sec

Configuration 5 α-cmd, ω_{sp} = 2, $1/\tau_{\theta_2}$ = .9

$$F = \begin{bmatrix} -1.0030 & .0652 & -5.4467 & .0205 \\ 1.0000 & .0000 & .0000 & .0000 \\ .3930 & -.0302 & -1.7197 & -.0085 \\ .0216 & -.8224 & .1894 & -.0973 \end{bmatrix} \qquad G = \begin{bmatrix} -1.0000 \\ .0000 \\ -.1500 \\ .0000 \end{bmatrix}$$

K_c = $-.65$

Nq = $-1\ (0)\ (.1)\ (.9)$

N_θ = $-1\ (.1)\ (.9)$

N_α = $-.15\ (3.7)\ [.1, .1]$

$Nn_{z_{cg}}$ = $-.018\ (0)\ (.089)\ (1.417)\ (-4.453)$

Nn_{z_p} = $-.0003\ (0)\ (.089)\ (1.597)\ (-241.4)$

D = $[.7, 2]\ [.1, .1]$

Time Delay = .16 sec

Configuration 6 q-cmd, $\omega_{sp} = 2,\ 1/\tau_{\theta_2} = .9$

$$F = \begin{bmatrix} -4.4000 & .0000 & .0000 & .0000 \\ 1.0000 & .0000 & .0000 & .0000 \\ -.1166 & -.0400 & -.9027 & -.0115 \\ .0216 & -.8224 & .1894 & -.0973 \end{bmatrix} \qquad G = \begin{bmatrix} -1.0000 \\ .0000 \\ -.1500 \\ .0000 \end{bmatrix}$$

$K_c = -.76$

$Nq = -1\ (0)\ (.1)\ (.9)$

$N_\theta = -1\ (.1)\ (.9)$

$N_\alpha = -.15\ (3.7)\ [.1,\ .1]$

$Nn_{z_{cg}} = -.018\ (0)\ (.089)\ (1.342)\ (-4.707)$

$Nn_{z_p} = -.0003\ (0)\ (.089)\ (1.476)\ (-261.4)$

$D = (0)\ (.1)\ (.9)\ (4.4)$

Time Delay $= .15$ sec

Configuration 7 Short term α-cmd/long term q-cmd, $\omega_{sp} = 2$, $1/\tau_{\theta_2} = .9$

$$F = \begin{bmatrix} -1.1634 & -.2828 & -4.9108 & -.0706 \\ 1.0000 & .0000 & .0000 & .0000 \\ .3689 & -.0824 & -1.6393 & -.0221 \\ .0216 & -.8224 & .1894 & -.0973 \end{bmatrix} \qquad G = \begin{bmatrix} -1.0000 \\ .0000 \\ -.1500 \\ .0000 \end{bmatrix}$$

$K_c = -.65$

$Nq = -1\ (0)\ (.1)\ (.9)$

$N_\theta = -1\ (.1)\ (.9)$

$N_\alpha = -.15\ (3.7)\ [.1,\ .1]$

$Nn_{z_{cg}} = -.018\ (0)\ (.089)\ (1.417)\ (-4.453)$

$N\dot{n}_{z_p} = -.0003\ (0)\ (.089)\ (1.597)\ (-241.4)$

$D = (0)\ (.1)\ [.7,\ 2]$

Time Delay $= .16$ sec

Configuration 8 Short term q-cmd/long term α-cmd, $\omega_{sp} = 2$, $1/\tau_{\theta_2} = .9$

$$F = \begin{bmatrix} -4.3232 & .3206 & .0216 & .0914 \\ 1.0000 & .0000 & .0000 & .0000 \\ -.1051 & .0081 & -.8995 & .0022 \\ .0216 & -.8224 & .1894 & -.0973 \end{bmatrix} \qquad G = \begin{bmatrix} -1.0000 \\ .0000 \\ -.1500 \\ .0000 \end{bmatrix}$$

K_c = $-.975$

Nq = $-1\ (0)\ (.1)\ (.9)$

N_θ = $-1\ (.1)\ (.9)$

N_α = $-.15\ (3.7)\ [.1, .1]$

$Nn_{z_{cg}}$ = $-.018\ (0)\ (.0893)\ (1.822)\ (-3.457)$

Nn_{z_p} = $-.0003\ (0)\ (.0892)\ (2.454)\ (-156.8)$

D = $(.9)\ (4.4)\ [.1, .1]$

Time Delay = .15 sec

Configuration 9 $\quad\alpha$-cmd uncoupled from phugoid, $\omega_{sp} = 2$, $1/\tau_{\theta_2} = .5$

$$F = \begin{bmatrix} -1.4094 & .0000 & -5.9376 & .0000 \\ 1.0000 & .0000 & .0000 & .0000 \\ .3436 & .0000 & -1.3906 & .0000 \\ -.1922 & -1.5000 & 1.6146 & -.1000 \end{bmatrix} \qquad G = \begin{bmatrix} -1.0000 \\ .0000 \\ -.1500 \\ .0000 \end{bmatrix}$$

$K_c \quad = -.65$

$Nq \quad = -1\ (0)\ (.1)\ (.5)$

$N_\theta \quad = -1\ (.1)\ (.5)$

$N_\alpha \quad = -.15\ (0)\ (.1)\ (3.7)$

$Nn_{z_{cg}} \quad = -.018\ (0)\ (.1)\ (.869)\ (-3.836)$

$Nn_{z_p} \quad = -.0003\ (0)\ (.1)\ (.959)\ (-211.9)$

$D \quad = (0)\ (.1)\ [.7, 2]$

Time Delay $\quad$ = .16 sec

Configuration 10 q-cmd uncoupled from phugoid, $\omega_{sp} = 2$, $1/\tau_{\theta_-} = .5$

$$F = \begin{bmatrix} -8.0000 & .0000 & .0000 & .0000 \\ 1.0000 & .0000 & .0000 & .0000 \\ -.6450 & .0000 & -.5000 & .0000 \\ -.1922 & -1.5000 & 1.6146 & -.1000 \end{bmatrix} \qquad G = \begin{bmatrix} -1.0000 \\ .0000 \\ -.1500 \\ .0000 \end{bmatrix}$$

$K_c = -.975$

$Nq = -1\ (0)\ (.1)\ (.5)$

$N_\theta = -1\ (.1)\ (.5)$

$N_\alpha = -.15\ (0)\ (.1)\ (3.7)$

$Nn_{z_{cg}} = -.018\ (0)\ (.1)\ (.869)\ (-3.836)$

$Nn_{z_p} = -.0003\ (0)\ (.1)\ (.959)\ (-211.9)$

$D = (0)\ (.1)\ (.5)\ (8)$

Time Delay = .15 sec

Configuration 11 $\dot{\gamma}$-cmd CR at Pilot Station 34′ fwd of CG, $\omega_{sp} = 2$, $1/\tau_{\theta_2} = .5$

$$F = \begin{bmatrix} -3.7598 & .3405 & -3.0348 & -.1796 \\ 1.0000 & .0000 & .0000 & .0000 \\ -.0005 & .0907 & -1.0519 & .0641 \\ -.1440 & -1.3427 & 1.2930 & -.0033 \end{bmatrix} \qquad G = \begin{bmatrix} -1.0000 \\ .0000 \\ -.1500 \\ .0000 \end{bmatrix}$$

also requires 2/(s + 2) prefilter

$K_c = -3.33$

$N_q = -1\ (0)\ (.1)\ (.5)$

$N_\theta = -1\ (.1)\ (.5)$

$N_\alpha = -.15\ (3.7)\ [.1, .3]$

$N_{n_{z_{cg}}} = -.018\ (0)\ (0)\ (.955)\ (-3.862)$

$N_{n_{z_p}} = -.0003\ (0)\ (0)\ (1.063)\ (-214.4)$

$D = (0)\ (0)\ (.955)\ (3.86)\ (2)$

Time Delay = .25 sec

Configuration 12 $\dot{\gamma}$-cmd CR at CG 34′ aft of pilot, $\omega_{sp} = 2$, $1/\tau_{\theta_2} = .5$

$$F = \begin{bmatrix} -2.2000 & .0815 & -4.8569 & -.3184 \\ 1.0000 & .0000 & .0000 & .0000 \\ .5550 & .0261 & -.5837 & -.0372 \\ .0500 & -1.3336 & 1.0891 & -.0163 \end{bmatrix} \qquad G = \begin{bmatrix} -1.0000 \\ .0000 \\ .0000 \\ .0000 \end{bmatrix}$$

also requires 1.274/(s + 1.274) prefilter

K_c = −2.12

Nq = −1 (0) (.1) (.5)

N_θ = −1 (.1) (.5)

N_α = −.555 [.1, .3]

$Nn_{z_{cg}}$ = −.054 (0) (0) (1.274)

Nn_{z_p} = −.018 (0) (0) [.917, 1.97]

D = (0) (0) (1.274) [.7, 2]

Time Delay = .29 sec

Configuration 13 α-cmd, $\omega_{sp} = 2$, $1/\tau_{\theta_2} = 2$

$$F = \begin{bmatrix} .6294 & -.1467 & -9.2630 & -.1766 \\ 1.0000 & .0000 & .0000 & .0000 \\ .6266 & -.0514 & -3.2772 & -.1602 \\ .2751 & -.4206 & -1.5010 & -.2122 \end{bmatrix} \qquad G = \begin{bmatrix} -1.0000 \\ .0000 \\ -.1500 \\ .0000 \end{bmatrix}$$

$K_c = -.65$

$N_q = -1\ (0)\ (.1)\ (2)$

$N_\theta = -1\ (.1)\ (2)$

$N_\alpha = -.15\ (3.7)\ [.1,\ .3]$

$Nn_{z_{cg}} = -.018\ (0)\ (.074)\ (2.47)\ (-545)$

$Nn_{z_p} = -.0003\ (0)\ (.074)\ (2.694)\ (-306.1)$

$D = [.7,\ 2]\ [.1,\ .3]$

Time Delay = .16 sec

Configuration 14 q-cmd, $\omega_{sp} = 2$, $1/\tau_{\theta_2} = 2$

$$F = \begin{bmatrix} -2.0000 & .0000 & .0000 & .0000 \\ 1.0000 & .0000 & .0000 & .0000 \\ .2322 & -.0294 & -1.8878 & -.1337 \\ .2761 & -.4206 & -1.5010 & -.2122 \end{bmatrix} \qquad G = \begin{bmatrix} -1.0000 \\ .0000 \\ -.1500 \\ .0000 \end{bmatrix}$$

$K_c = -.65$

$Nq = -1\ (0)\ (.1)\ (2)$

$N_\theta = -1\ (.1)\ (2)$

$N_\alpha = -.15\ (3.7)\ [.1, .3]$

$Nn_{z_{cg}} = -.018\ (0)\ (.074)\ (2.47)\ (-545)$

$Nn_{z_p} = -.0003\ (0)\ (.074)\ (2.694)\ (306.1)$

$D = (0)\ (.1)\ (2)\ (2)$

Time Delay = .16 sec

Configuration B   Baseline conventional airplane, $\omega_{sp} = 2,\ 1/\tau_{\theta_2} = .75$

$$F = \begin{bmatrix} -1.9000 & .0000 & -2.2900 & .0246 \\ 1.0000 & .0000 & .0000 & .0000 \\ 1.0000 & .0000 & -.9010 & -.0711 \\ .0000 & -.5614 & .2618 & -.0382 \end{bmatrix} \qquad G = \begin{bmatrix} -1.9500 \\ .0000 \\ -.1010 \\ -.0326 \end{bmatrix}$$

$K_c = -.275$

$Nq = -1.95\ (0)\ (.067)\ (.753)$

$N_\theta = -1.95\ (.067)\ (.753)$

$N_\alpha = -.101\ (21.19)\ [.032,\ .577]$

$Nn_{z_{cg}} = -.012\ (.0145)\ (4.951)\ (-3.051)$

$Nn_{z_p} = -.011\ (.0144)\ [-.004,\ 4.109]$

$D = [.7,\ 2]\ [.112,\ .14]$

Time Delay = .15 sec

APPENDIX C

This appendix presents the tabulated data used for the various criteria discussed in this study.

TABLE C.1 Equivalent Systems Match Results —
Simultaneous q and n_{zp} Match

$1/T_{\theta_2}$ FIXED

CASE	ω_{sp}	ζ_{sp}	$1/T_{\theta_2}$	$1/\tau_\alpha$	TIME DELAY	MISMATCH	
1	1.933	0.830	0.5	3.7	0.000	334.290	+
2	2.020	0.961	0.5	3.7	0.000	190.200	+
3	1.920	0.696	0.5	3.7	0.000	2.958	
4	0.464	0.486	0.5	3.7	0.000	364.000	+
5	1.416	0.866	0.9	3.7	0.000	367.180	
6	1.987	1.316	0.9	3.7	0.000	0.043	
7	2.498	0.724	0.9	3.7	0.000	81.560	+
8	1.827	1.505	0.9	3.7	0.000	4.596	
9	2.000	0.700	0.5	3.7	0.000	0.000	
10	1.995	2.115	0.5	3.7	0.007	0.006	
11	0.928	0.940	0.5	3.7	0.121	135.100	
12	0.870	0.945	0.5	3.7	0.163	270.015	
13	1.930	0.873	2	3.7	0.000	330.800	+
14	1.994	0.969	2	3.7	0.000	0.299	
B	1.129	0.787	0.75	21.19	0.000	1047.500	

$1/T_{\theta_2}$ FREE

CASE	ω_{sp}	ζ_{sp}	$1/T_{\theta_2}$	$1/\tau_\alpha$	TIME DELAY	MISMATCH	
1	1.877	0.771	0.000	3.7	0.000	247.000	
2	2.895	1.106	1.306	3.7	0.000	21.620	+
3	NA	NA	NA	NA	NA	NA	
4	NA	NA	NA	NA	NA	NA	
5	NA	NA	NA	NA	NA	NA	
6	NA	NA	NA	NA	NA	NA	
7	2.479	0.663	1.452	3.7	0.000	11.386	
8	NA	NA	NA	NA	NA	NA	
9	NA	NA	NA	NA	NA	NA	
10	NA	NA	NA	NA	NA	NA	
11	2.380	0.822	4.870	3.7	0.092	18.937	
12	NA	NA	NA	NA	NA	NA	
13	NA	NA	NA	NA	NA	NA	
14	NA	NA	NA	NA	NA	NA	
B	NA	NA	NA	NA	NA	NA	

+ = .3 — 10 rad/sec Frequency Range

NA = Not Applicable

TABLE C.2 Equivalent Systems Match Results — Simultaneous q and $n_{z_{cg}}$ Match

$1/T_{\theta_2}$ FIXED

CASE	ω sp	ζ_{sp}	$1/T_{\theta_2}$	$1/\tau\alpha$	TIME DELAY	MISMATCH	
1	1.907	0.786	0.5	3.7	0.000	332.000	
2	1.998	2.018	0.5	3.7	0.000	0.659	+
3	1.920	0.694	0.5	3.7	0.000	2.890	
4	2.144	0.823	0.5	3.7	0.000	3056.000	+
5	1.923	0.769	0.9	3.7	0.000	8.670	+
6	1.987	1.317	0.9	3.7	0.000	0.040	
7	3.120	0.764	0.9	3.7	0.000	301.900	
8	1.822	1.500	0.9	3.7	0.000	4.620	+
9	1.998	0.700	0.5	3.7	0.000	0.000	
10	11.440	5.733	0.5	3.7	0.042	468.800	
11	0.895	0.764	0.5	3.7	0.000	356.400	+
12	1.078	0.506	0.5	3.7	0.000	244.000	
13	1.706	0.707	2	3.7	0.000	317.500	+
14	2.000	0.984	2	3.7	0.000	0.085	
B	1.070	1.448	0.75	21.2	0.000	486.800	

$1/T_{\theta_2}$ FREE

CASE	ω sp	ζ_{sp}	$1/T_{\theta_2}$	$1/\tau\alpha$	TIME DELAY	MISMATCH	
1	1.953	0.755	0.767	3.7	0.000	306.000	
2	NA	NA	NA	NA	NA	NA	
3	NA	NA	NA	NA	NA	NA	
4	3.797	1.597	22.800	3.7	0.000	557.800	+
5	NA	NA	NA	NA	NA	NA	
6	NA	NA	NA	NA	NA	NA	
7	1.930	0.730	0.822	3.7	0.000	0.270	+
8	NA	NA	NA	NA	NA	NA	
9	NA	NA	NA	NA	NA	NA	
10	8.910	1.730	4.026	3.7	0.000	4.890	
11	2.503	0.826	6.080	3.7	0.083	15.550	+
12	2.043	0.554	5.273	3.7	0.098	270.000	
13	NA	NA	NA	NA	NA	NA	
14	2.240	1.002	2.500	3.7	0.000	0.000	
B	NA	NA	NA	NA	NA	NA	

+ = .3 — 10 rad/sec Frequency Range

NA = Not Applicable

TABLE C.3 Equivalent Systems Match Results — q only Match

$1/T_{\theta_2}$ FIXED

CASE	ω_{sp}	ζ_{sp}	$1/T_{\theta_2}$	$1/\tau_\alpha$	TIME DELAY	MISMATCH	
1	1.673	0.890	0.5	3.7	0.000	299.000	+
2	2.044	2.129	0.5	3.7	0.000	0.002	
3	2.044	0.727	0.5	3.7	0.000	0.927	
4	0.538	0.712	0.5	3.7	0.000	275.000	+
5	1.908	0.771	0.9	3.7	0.000	8.620	+
6	1.999	1.332	0.9	3.7	0.000	0.000	
7	2.044	0.727	0.9	3.7	0.000	0.927	
8	1.853	1.533	0.9	3.7	0.000	4.740	
9	2.044	0.727	0.5	3.7	0.000	0.927	
10	2.052	2.217	0.5	3.7	0.000	0.780	
11	0.928	0.723	0.5	3.7	0.123	55.230	+
12	0.968	0.743	0.5	3.7	0.160	61.450	
13	1.673	0.890	2	3.7	0.000	285.000	+
14	1.999	0.999	2	3.7	0.000	0.000	
B	1.928	0.755	0.75	21.2	0.000	4.300	

$1/T_{\theta_2}$ FREE

CASE	ω_{sp}	ζ_{sp}	$1/T_{\theta_2}$	$1/\tau_\alpha$	TIME DELAY	MISMATCH	
1	NA	NA	NA	NA	NA	NA	
2	NA	NA	NA	NA	NA	NA	
3	NA	NA	NA	NA	NA	NA	
4	0.467	0.748	0.070	3.7	0.000	4.180	+
5	NA	NA	NA	NA	NA	NA	
6	NA	NA	NA	NA	NA	NA	
7	NA	NA	NA	NA	NA	NA	
8	0.813	5.641	0.246	3.7	0.000	0.140	
9	NA	NA	NA	NA	NA	NA	
10	NA	NA	NA	NA	NA	NA	
11	NA	NA	NA	NA	NA	NA	
12	2.294	0.488	8.661	3.7	0.073	34.670	
13	NA	NA	NA	NA	NA	NA	
14	NA	NA	NA	NA	NA	NA	
B	2.174	0.667	1.066	21.190	0.000	2.541	

+ = .3 — 10 rad/sec Frequency Range

NA = Not Applicable

TABLE C.4 Equivalent Systems Match Results —
α Only Match

$1/T_\alpha$ FIXED

CASE	ω_{sp}	ζ_{sp}	$1/T_{\theta_2}$	$1/\tau_\alpha$	TIME DELAY	MISMATCH	
1	1.999	0.699	0.5	3.7	0.000	0.007	
2	2.565	1.622	0.5	3.7	0.000	307.000	+
3	2.283	0.556	0.5	3.7	0.000	308.400	+
4	1.999	2.124	0.5	3.7	0.000	0.000	
5	2.000	0.700	0.9	3.7	0.000	0.000	
6	2.125	2.391	0.9	3.7	0.000	5.470	+
7	2.078	0.641	0.9	3.7	0.000	8.874	+
8	2.006	1.353	0.9	3.7	0.000	0.265	
9	2.000	0.700	0.5	3.7	0.000	0.000	
10	2.000	0.700	0.5	3.7	0.000	0.001	
11	1.183	0.585	0.5	3.7	0.000	684.300	+
12	1.297	0.474	0.5	3.7	0.174	449.200	+
13	2.000	0.700	2	3.7	0.000	0.000	
14	2.359	0.784	2	3.7	0.000	282.900	
B	1.323	0.180	0.75	21.2	0.000	2545.500	

$1/T_\alpha$ FREE

CASE	ω_{sp}	ζ_{sp}	$1/T_{\theta_2}$	$1/\tau_\alpha$	TIME DELAY	MISMATCH	
1	NA	NA	NA	NA	NA	NA	
2	NA	NA	NA	NA	NA	NA	
3	1.834	0.509	0.5	1.950	0.000	285.000	+
4	NA	NA	NA	NA	NA	NA	
5	NA	NA	NA	NA	NA	NA	
6	NA	NA	NA	NA	NA	NA	
7	NA	NA	NA	NA	NA	NA	
8	NA	NA	NA	NA	NA	NA	
9	NA	NA	NA	NA	NA	NA	
10	NA	NA	NA	NA	NA	NA	
11	NA	NA	NA	NA	NA	NA	
12	NA	NA	NA	NA	NA	NA	
13	NA	NA	NA	NA	NA	NA	
14	NA	NA	NA	NA	NA	NA	
B	NA	NA	NA	NA	NA	NA	

+ = .3 — 10 rad/sec Frequency Range

NA = Not Applicable

TABLE C.5 Equivalent Systems Match Results —
Two Part $\propto$ then q Match

CASE	ω_{sp}	ζ_{sp}	$1/T_{\theta_2}$	$1/\tau_\alpha$	TIME DELAY	MISMATCH
1	1.990	0.699	0.853	3.7	0.0	309.00
2	2.565	1.622	0.877	3.7	0.0	0.41
3	2.228	0.556	1.378	3.7	0.0	295.00
4	1.999	2.124	7.936	3.7	0.0	309.00
5	2.000	0.700	1.057	3.7	0.0	6.86
6	2.125	2.391	0.646	3.7	0.0	68.70
7	2.078	0.641	0.982	3.7	0.0	1.50
8	2.006	1.353	1.045	3.7	0.0	6.32
9	2.000	0.700	0.500	3.7	0.0	0.00
10	2.000	0.700	0.944	3.7	0.0	228.00
11	1.183	0.585	1.015	3.7	0.0	268.00
12	1.293	0.474	1.628	3.7	0.0	447.00
13	2.000	0.700	2.889	3.7	0.0	323.00
14	2.359	0.748	2.975	3.7	0.0	28.00
B	NA	NA	NA	NA	NA	NA

NA = Not Applicable

TABLE C.6 Data for Transient Peak Ratio, Rise Time, Effective Delay Criterion

CONFIG.	t_1	Δt	$\Delta q_2 / \Delta q_1$
1 *	.06	.20	.08
2	.06	.20	(%) $\zeta = 2.1$
3	.06	.22	.07
4 *	.06	.25	(%) $\zeta = 2.1$
5	.06	.40	.33
6	.06	.24	(%) $\zeta = 1.3$
7	.06	.23	0
8 *	.06	.38	(%) $\zeta = 1.3$
9	.06	.22	.11
10	.06	.24	(%) $\zeta = 2.1$
11	.19	.83	−3.0
12	.20	.86	−.29
13 *	.06	.60	0
14	.06	.63	(%) $\zeta = 1$
B	.06	.25	.15

* - Short Period Approximation

(%) - Applied MIL-F-8758C Requirements for $\zeta \geqslant 1$

TABLE C.7 Data for Bandwidth Criterion

CONFIG.	$\omega_{BW_{GAIN}}$	$\omega_{BW_{PHASE}}$	$\omega_1 = 2\,\omega_{180}$	ϕ_1	$\tau_p = \frac{-\phi_1 - 180}{57.3\,\omega_1}$	ω_{BW}
1	2.7	2.3	8.0	−236.25	.123	2.3
2	3.4	3.3	12.0	−255	.109	3.3
3	2.7	2.25	8.0	−236.25	.123	2.25
4	2.3	3.25	12.5	−242.5	.087	2.3
5	2.3	2.1	6.7	−223.75	.114	2.1
6	2.8	2.3	10.0	−242.2	.109	2.3
7	2.3	2.1	6.7	−223.75	.114	2.1
8	2.3	2.0	9.8	−242.5	.117	2.0
9	2.4	2.25	8.0	−236.25	.123	2.25
10	3.1	3.0	12.0	−255	.109	3.0
11	1.3	1.1	4.0	−230	.220	1.1
12	0.9	1.1	3.7	−274.6	.308	1.1
13	2.1	1.4	5.4	−217.5	.121	1.4
14	2.2	1.3	6.4	−220	.109	1.3
B	2.3	2.1	7.4	−230	.118	2.1

TABLE C.8 Closed-Loop Pilot Models

CONFIG.	Kp GAIN	PHASE (deg)	τ_{p_1} (sec)	τ_{p_2} (sec)
1	4.92	35	0.77	0.21
2	7.69	40	0.86	0.19
3	4.83	10	0.48	0.34
4	3.11	10	0.48	0.34
5	1.99	25	0.63	0.25
6	3.27	25	0.63	0.25
7	2.09	25	0.63	0.25
8	2.77	30	0.69	0.25
9	1.72	15	0.52	0.31
10	3.22	10	0.48	0.34
11	2.86	50	1.01	0.15
12	9.93	65	1.80	0.09
13	2.99	50	1.01	0.15
14	4.79	55	1.27	0.13
BASE	2.65	25	0.63	0.25

TABLE C.9 Data for Gibson's Criterion

CONFIG.	DROP BACK/q	t_{n_z} (sec)	ω_{120} (Hz)	ω_{180} (Hz)	$\dot{\phi}$ ($^{deg}/H_z$)	GAIN ω_{180} ($^{deg}/_{lb}$)
1	−0.53	0.74	0.303	0.634	122.15	0.405
2	−0.4	1.00	0.303	1.004	82.73	.0152
3	−0.8	0.32	0.303	0.634	122.01	.0428
4	0.67	0.79	0.303	1.004	77.74	.0152
5	−0.13	1.32	0.252	0.578	124.49	.0489
6	−0.53	1.63	0.238	0.762	91.38	.0292
7	0.27	0.74	0.277	0.634	126.79	.0489
8	−1.33	4.58	0.199	0.762	90.10	.0314
9	1.07	0.53	0.303	0.634	122.01	.0427
10	−0.27	4.32	0.303	1.004	82.73	.0152
11	−2.67	2.26	0.110	0.303	272.40	.1362
12	−1.33	1.42	0.132	0.277	421.80	.2069
13	4	1.11	0.175	0.459	136.36	.0877
14	−1.87	1.37	0.132	0.527	105.64	.0594
B	0.8	UND	0.277	0.634	118.74	.0336

TABLE C.10 Time Domain Criterion Data

CONFIG	1.7 $\dot{\alpha}'$	$-1.44\ N_{\dot{z}_p}$	0.55 $T\dot{\alpha}'$	TDq	TD′	$\dot{q}'$	PHQR	AHQR
1	0	0	0.11	160	1.33	.25	3.69	2.9
2	0.49	0	0	150	1.11	.25	3.85	4.0
3	0.17	0	0	160	1.33	.25	3.75	3.7
4	0.19	0	0	140	0.89	.25	3.33	3.3
5	0	0	0	160	1.33	.25	3.58	5.0
6	0	0	0	150	1.11	.25	3.36	2.3
7	0	0	0	160	1.33	.25	3.58	4.0
8	0.07	0	0.10	150	1.11	.25	3.53	2.0
9	0	0	0	160	1.33	.25	3.58	4.0
10	0.15	0	0	150	1.11	.25	3.51	2.8
11	1.0	0	3.3	250	3.33	.25	9.88	7.5
12	0.85	0	3.3	290	4.22	.25	10.62	7.5
13	0	0	0	1.60	1.33	.25	3.58	7.3
14	0.34	0	0	160	1.33	.25	3.92	4.5
B	0	−0.58	0	150	1.11	0.15	2.7	2.6

PHQR = Predicted Handling Qualities Rating
AHQR = Average Handling Qualities Rating (Flared Landing)

APPENDIX D

This appendix presents the plotted results of the various criteria used in this study. The plots presented are as follows:

D.1 Equivalent System Results —

CAP vs ζ_{sp}

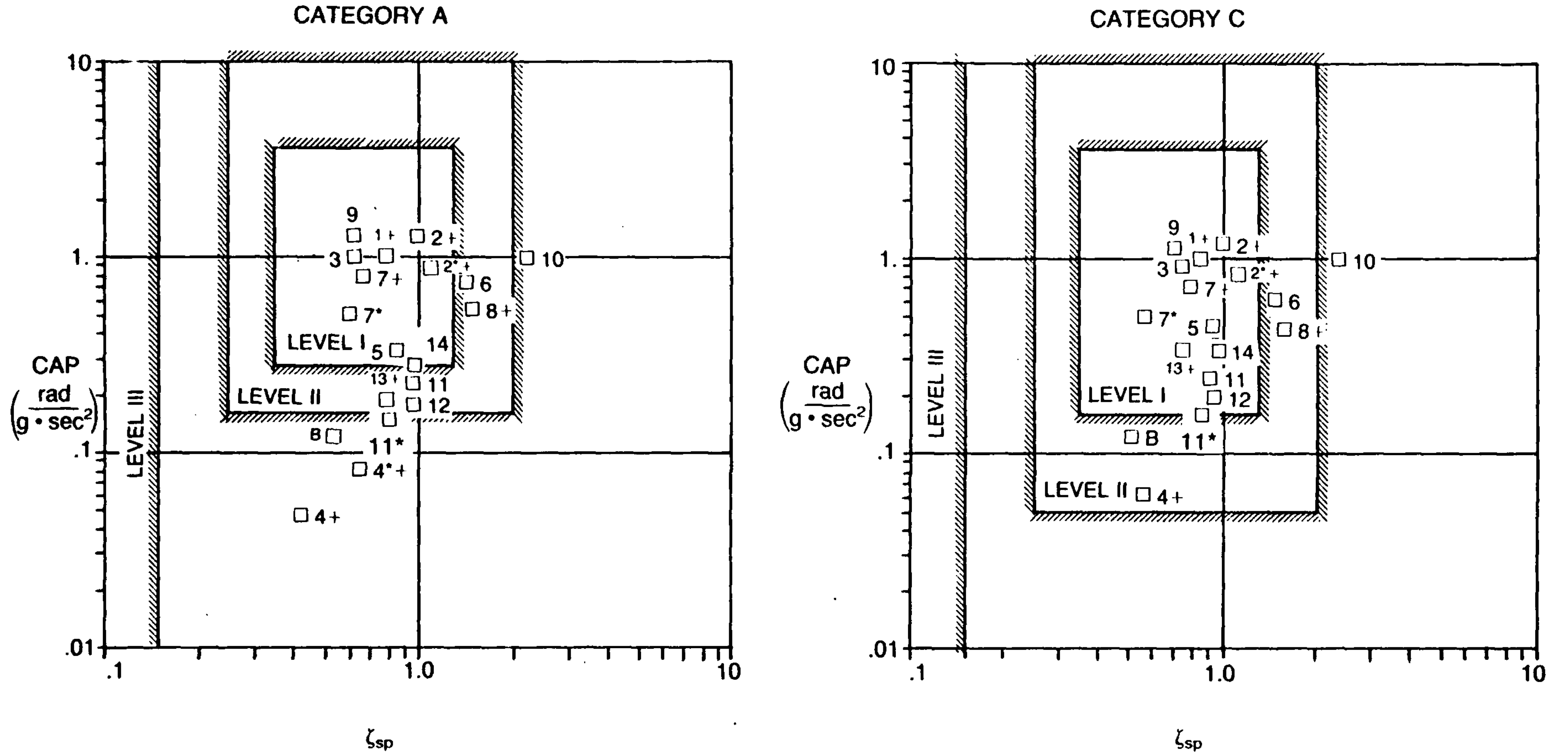
$\omega_{sp} T_{\theta_2}$ vs ζ_{sp}

ω_{sp} vs n/α

D.2 Closed-Loop θ/θ_c Bode Plots

D.3 Normalized n_z Response

D.4 Optimum Attitude Response



* $1/T_{\theta_2}$ Free
\+ Freq. Range .3-10 rad/sec
B 1, 2 . . . Configuration No.

FIGURE D.1.1 CAP VS. ζ_{sp} —
SIMULTANEOUS q/F_s AND n_{z_p}/F_s
EQUIVALENT SYSTEM MATCH

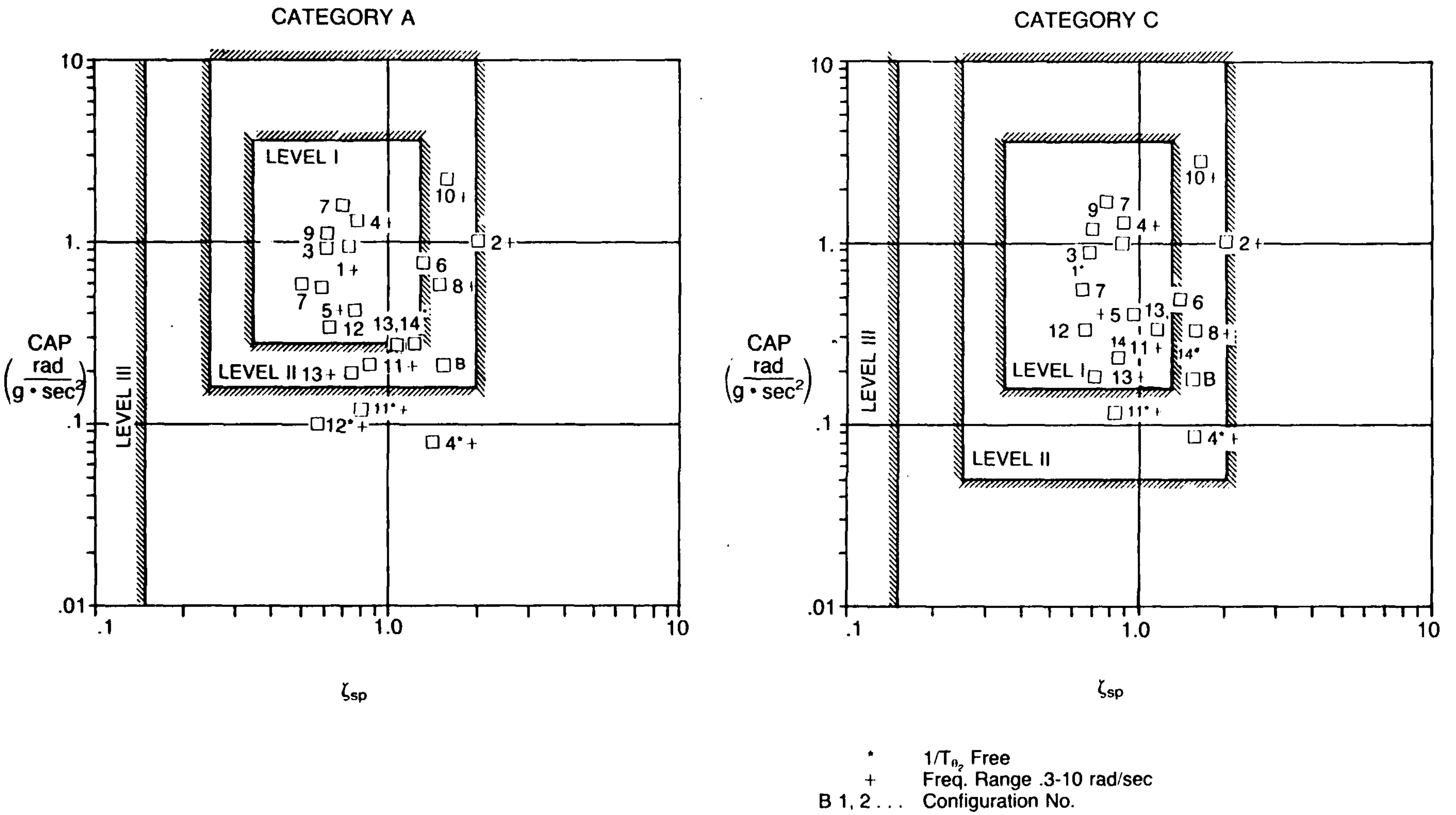
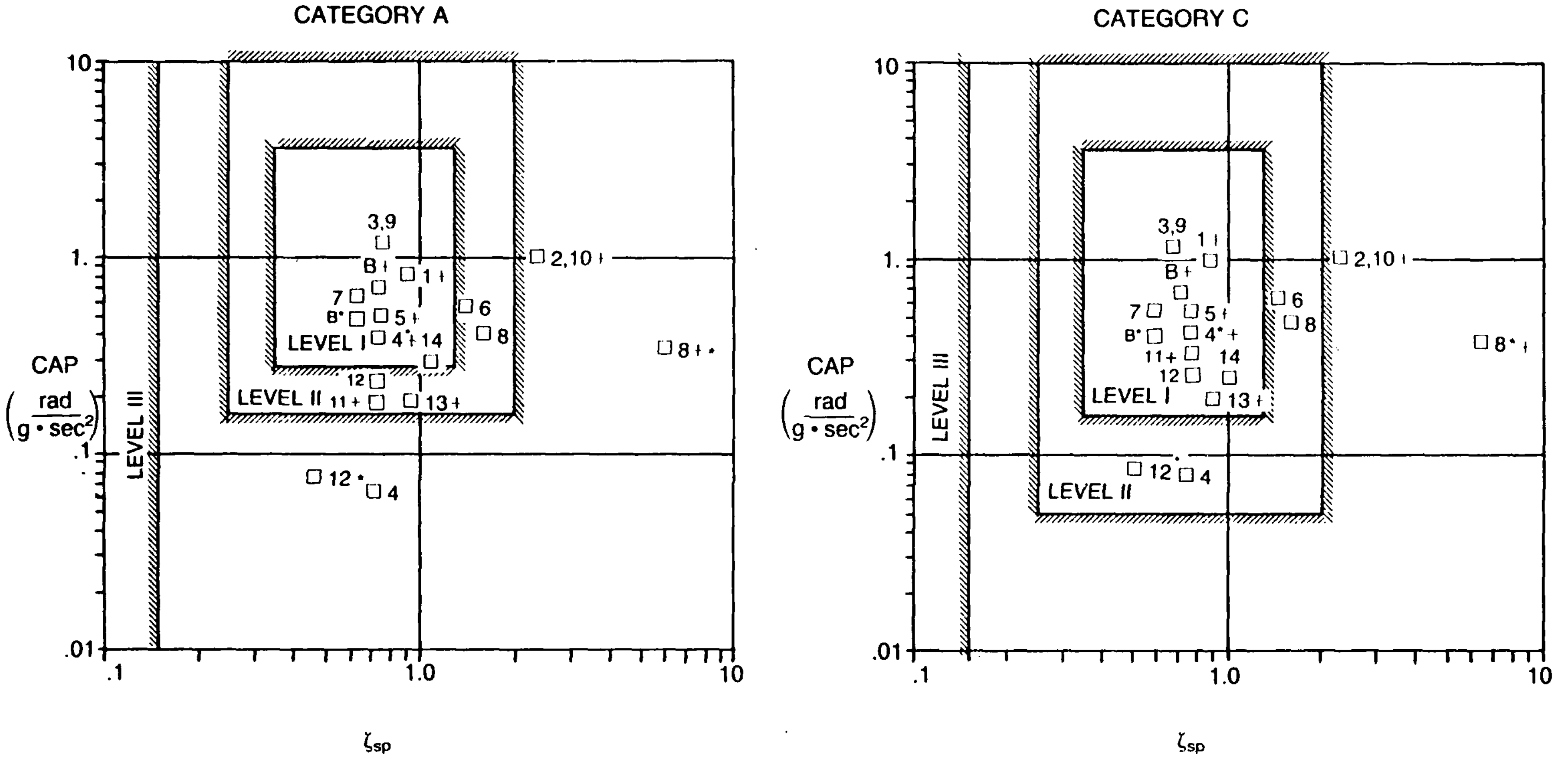


FIGURE D.1.2 CAP VS. ζ_{sp}—
SIMULTANEOUS q/F_s AND $n_{z_{cp}}/F_s$
EQUIVALENT SYSTEM MATCH

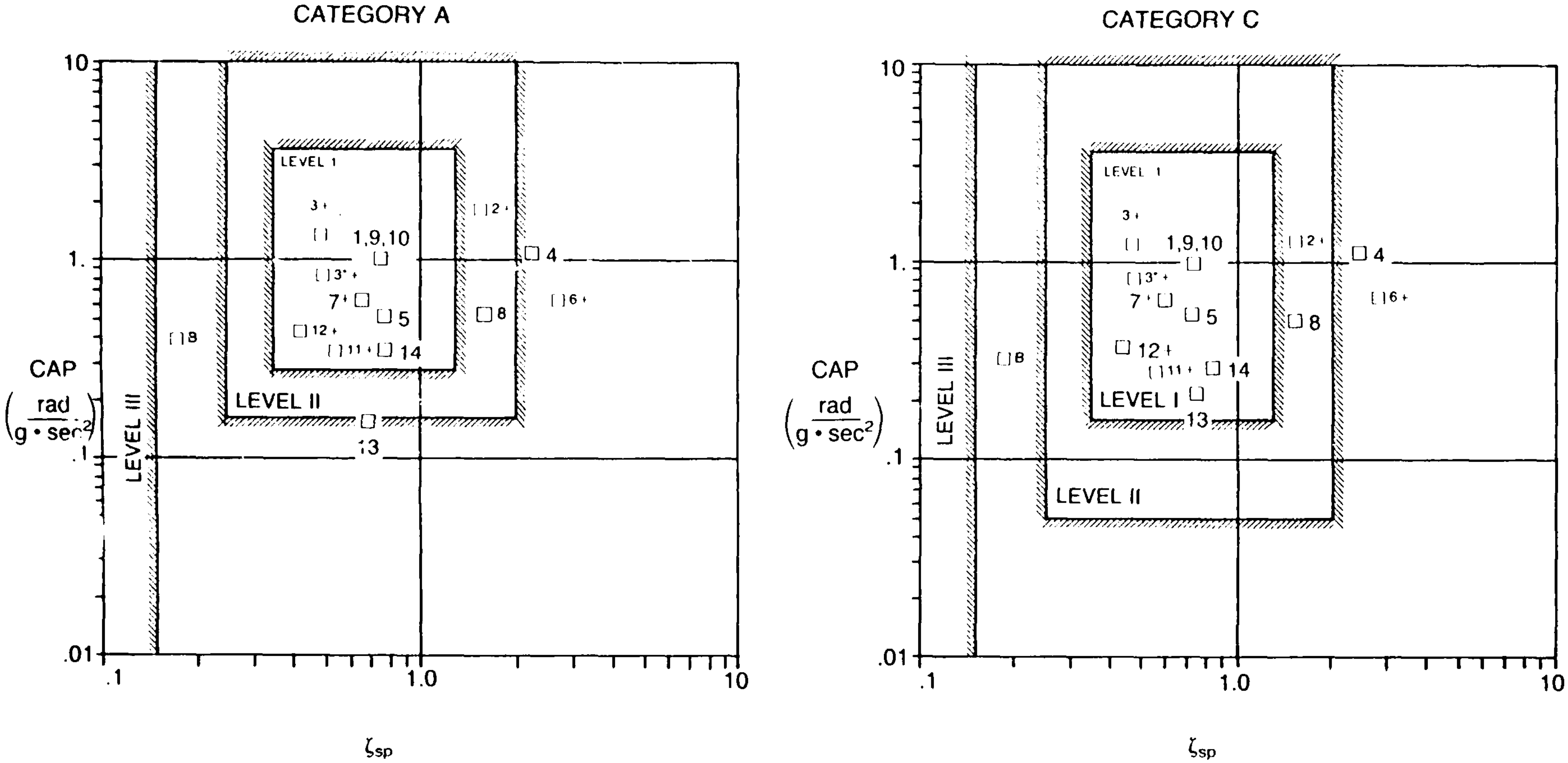


* 1/T_{θ_2} Free

\+ Freq. Range .3-10 rad/sec

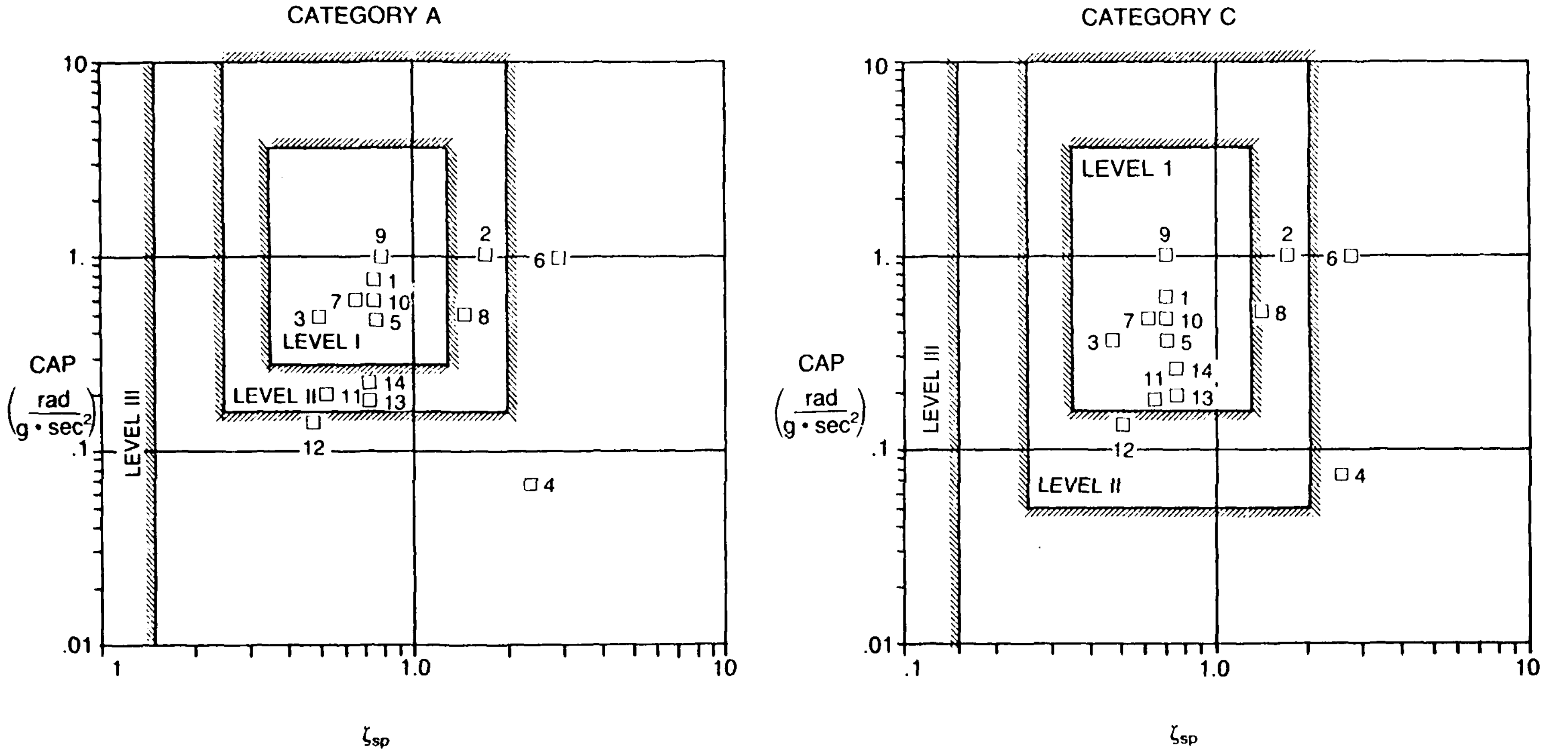
B 1, 2 . . . Configuration No.

FIGURE D.1.3 CAP VS. ζ_{sp} —
q/F_s EQUIVALENT SYSTEM MATCH



* $1/T_{\theta_2}$ Free
\+ Freq. Range .3-10 rad/sec
B 1, 2 . . . Configuration No.

FIGURE D.1.4 CAP VS. ζ_{sp} —
α/F_s EQUIVALENT SYSTEM MATCH



* $1/T_{\theta_2}$ Free
\+ Freq. Range .3-10 rad/sec
B 1, 2 . . . Configuration No.

FIGURE D.1.5 CAP VS. ζ_{sp} —
TWO PART α/F_s THEN q/F_s
EQUIVALENT SYSTEM MATCH

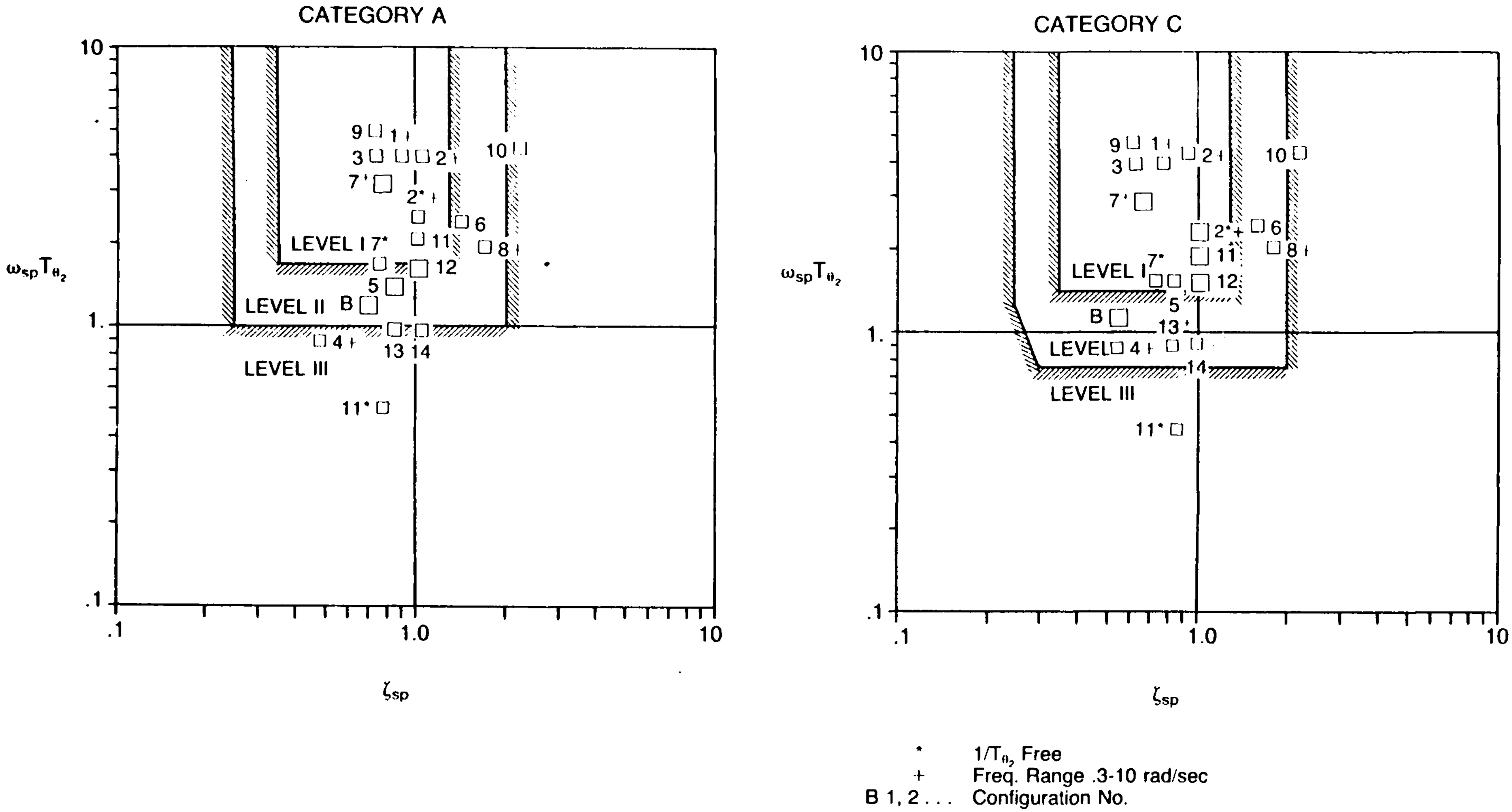
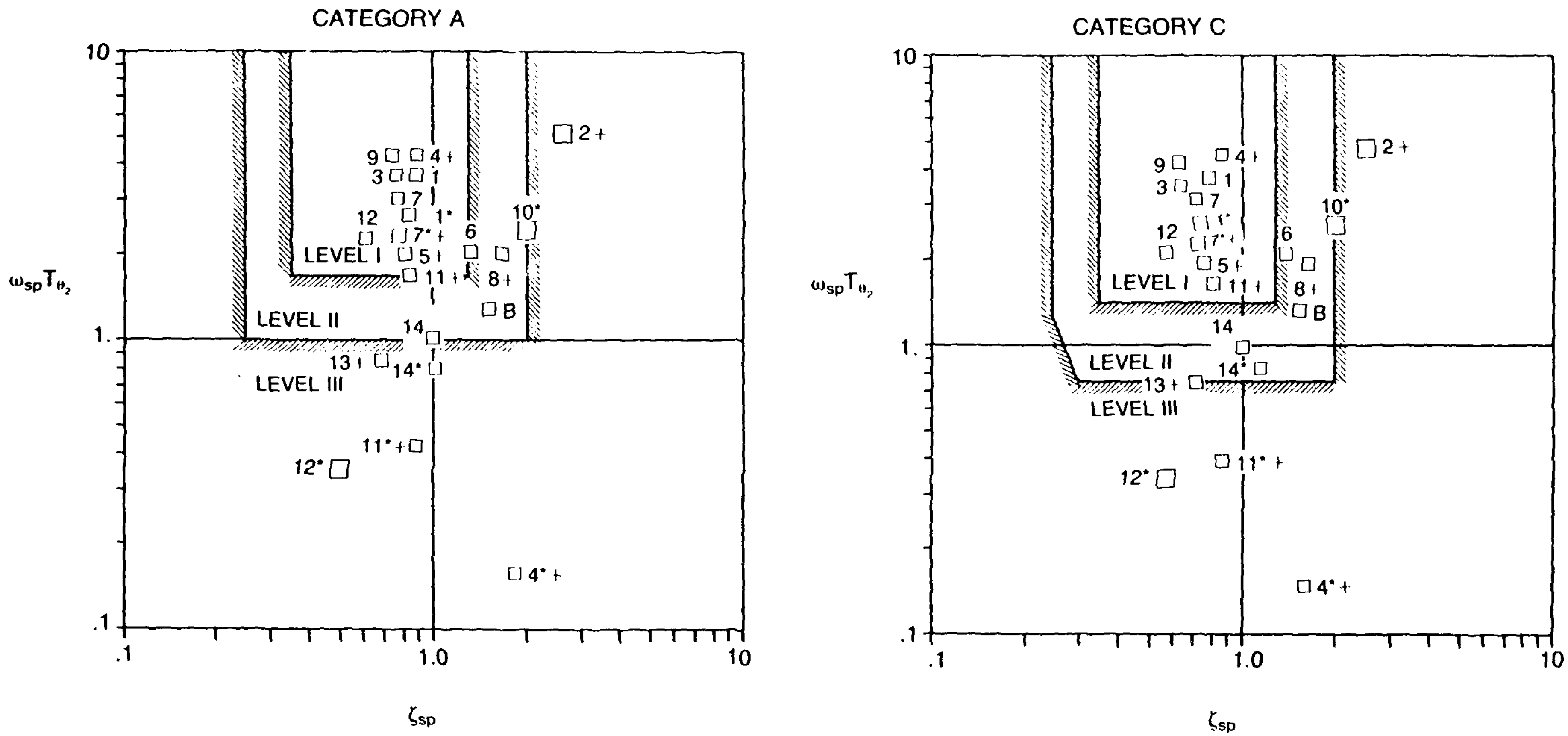


FIGURE D.1.6 $\omega_{sp}T_{\theta_2}$ vs ζ_{sp} — SIMULTANEOUS q/F_s AND n_{zp}/F_s EQUIVALENT SYSTEM MATCH



* $1/T_{\theta_2}$ Free
\+ Freq. Range .3-10 rad/sec
B 1, 2 . . . Configuration No.

FIGURE D.1.7 $\omega_{sp}T_{\theta_2}$ vs ζ_{sp} —
SIMULTANEOUS q/F_s AND $n_{z_{cg}}/F_s$
EQUIVALENT SYSTEM MATCH

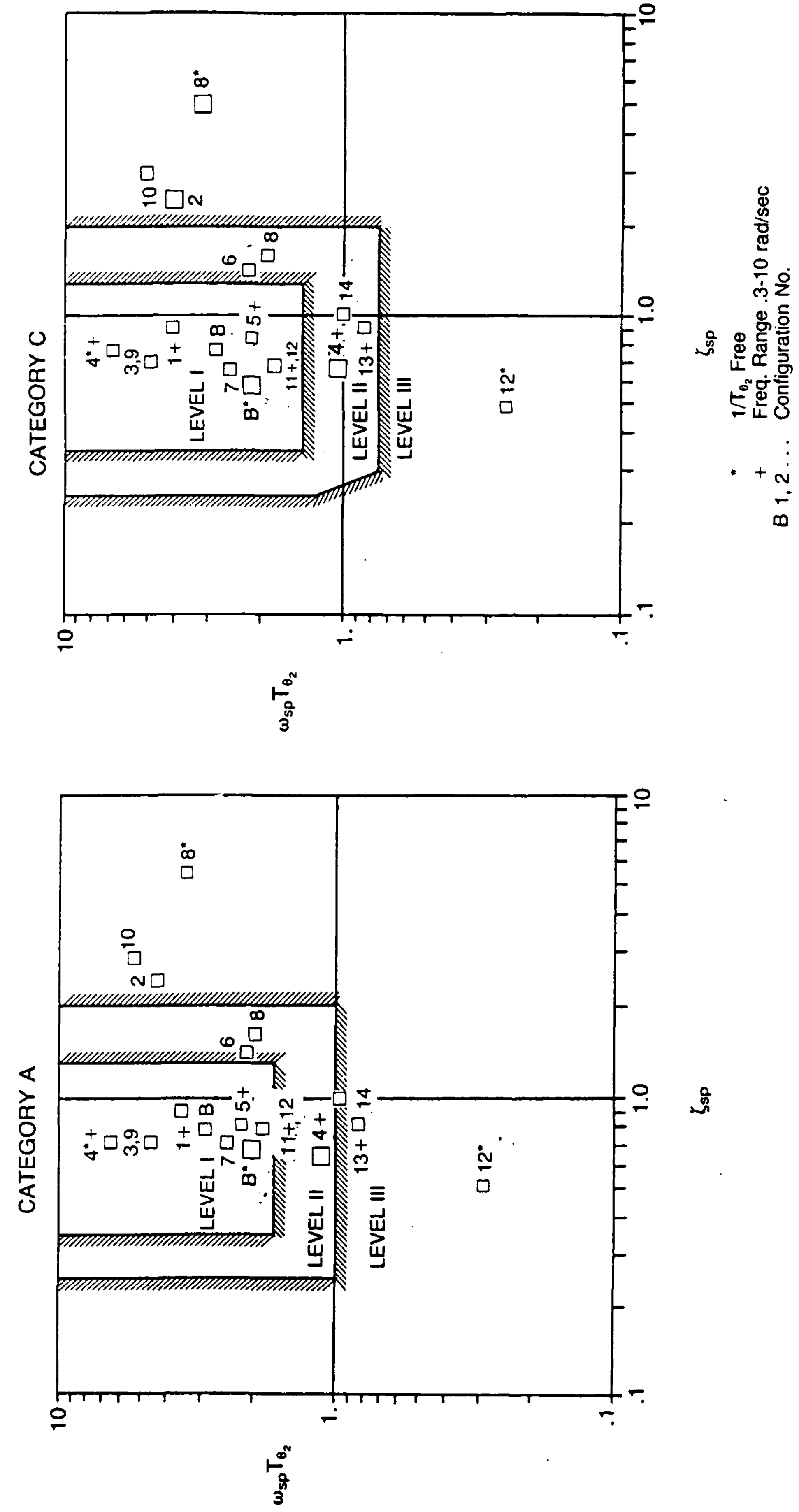


FIGURE D.1.8 $\omega_{sp} T_{\theta_2}$ VS ζ_{sp} —
q/F_s EQUIVALENT SYSTEM MATCH

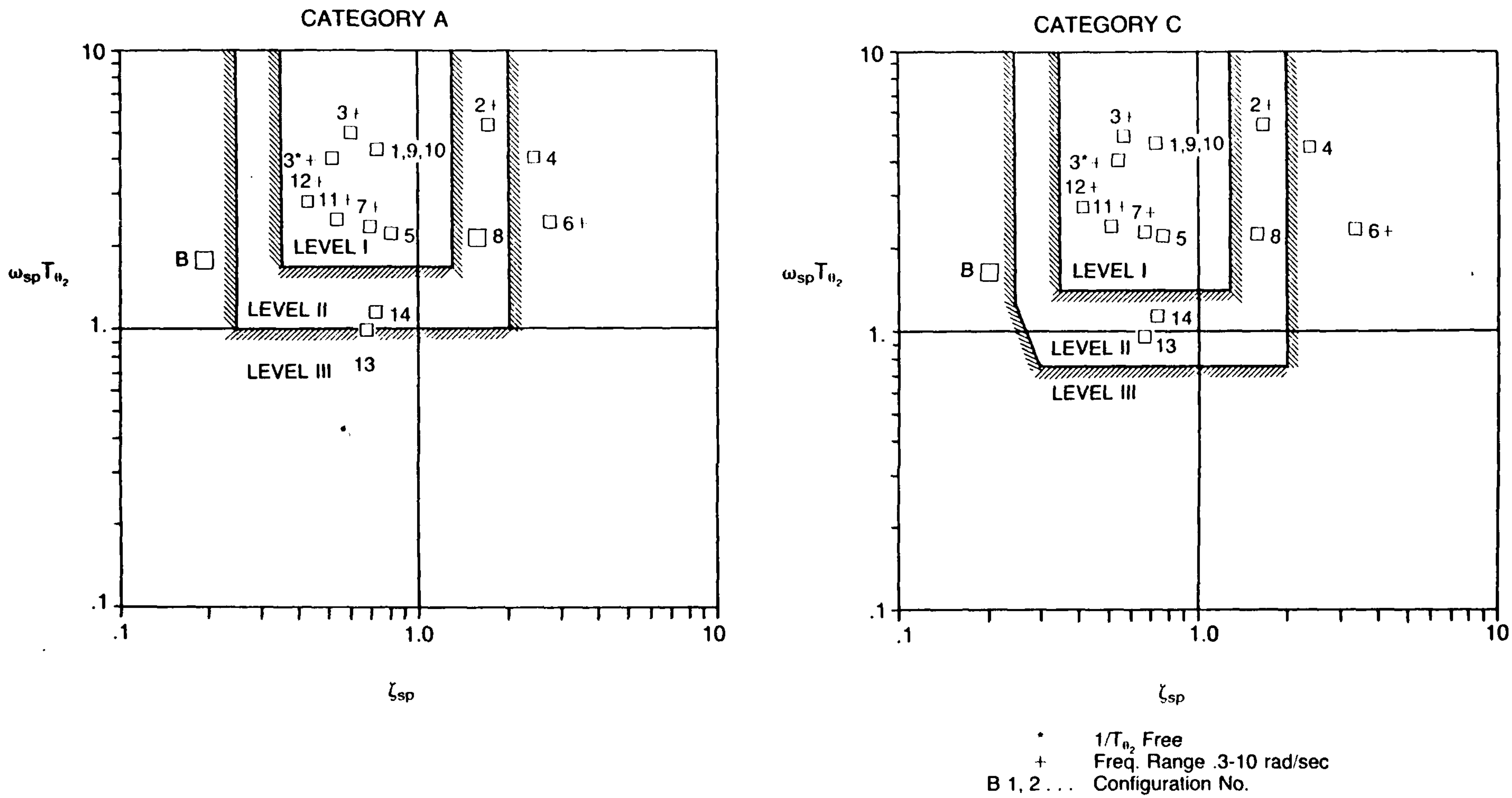
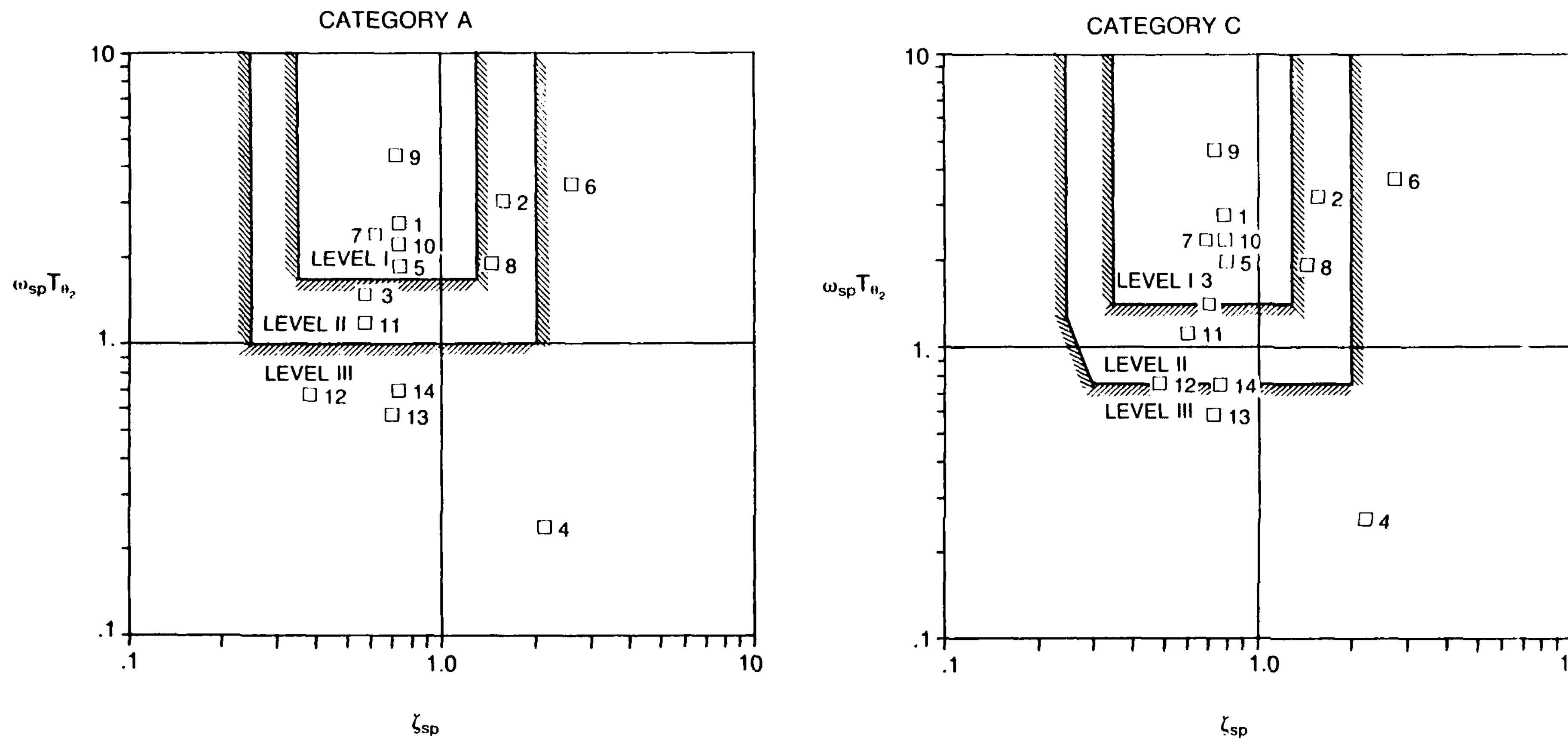


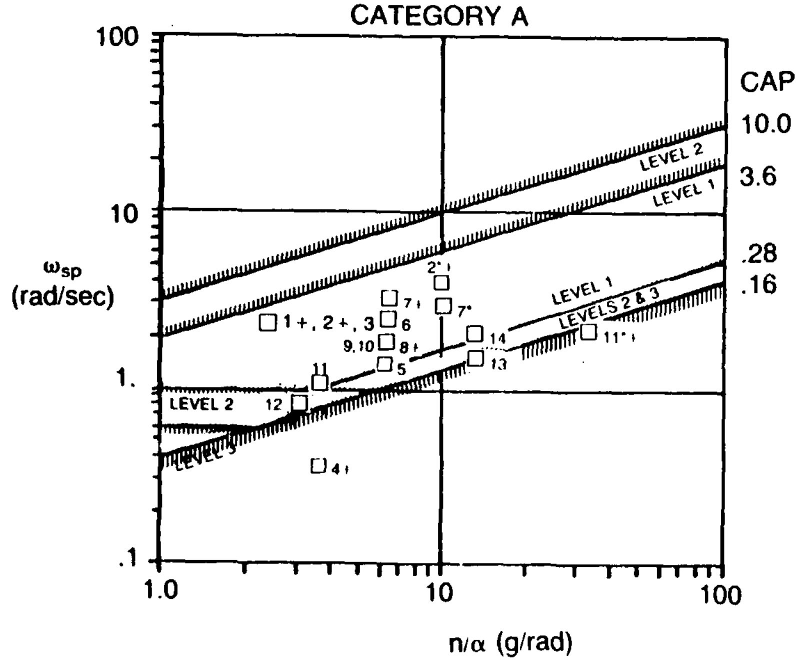
FIGURE D.1.9 $\omega_{sp}T_{\theta_2}$ vs ζ_{sp} —
α/F_s EQUIVALENT SYSTEM MATCH

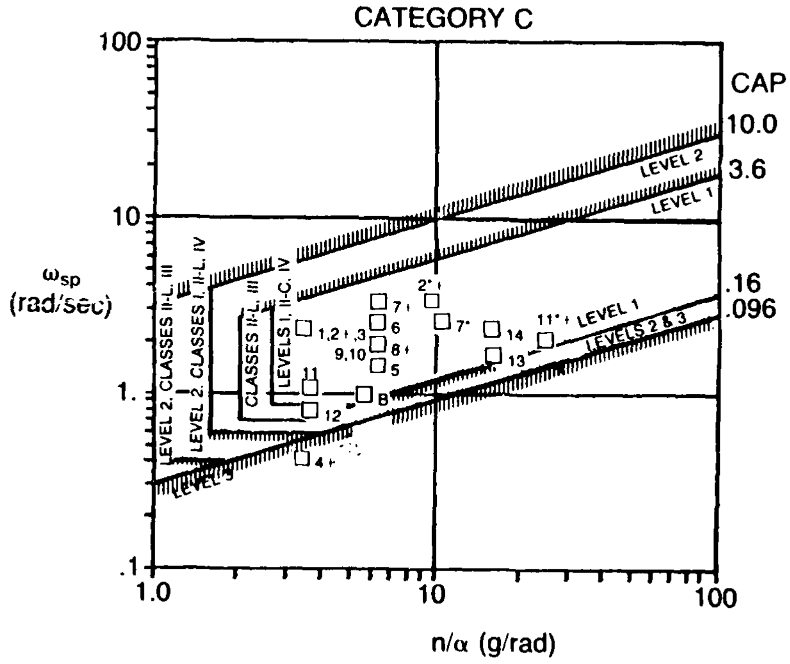


* $1/T_{\theta_2}$ Free
\+ Freq. Range .3-10 rad/sec
B 1, 2 . . . Configuration No.

5

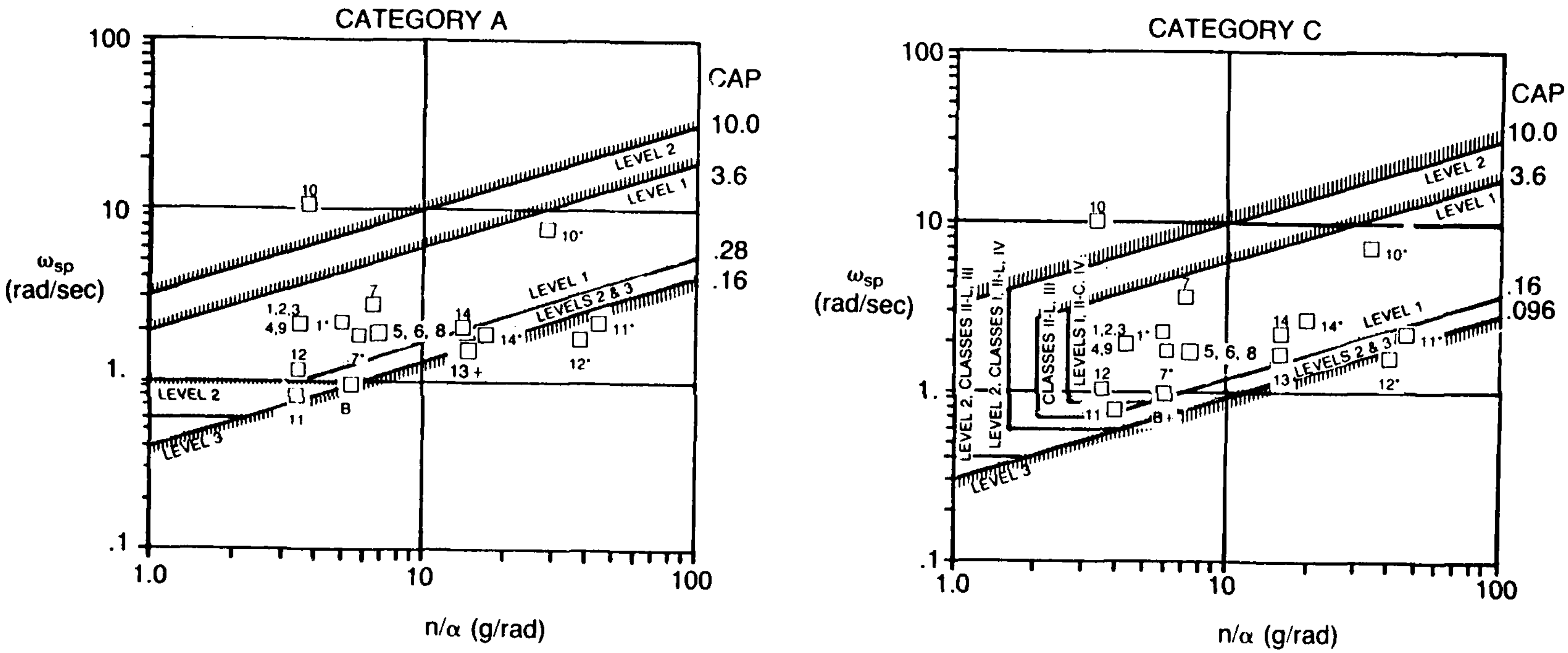
FIGURE D.1.10 $\omega_{sp}T_{\theta_2}$ vs ζ_{sp} —
TWO PART α/F_s THEN q/F_s
EQUIVALENT SYSTEM MATCH





*	$1/T_{\theta_2}$ Free
+	Freq. Range .3-10 rad/sec
B 1, 2 . . .	Configuration No.

FIGURE D.1.11 ω_{sp} vs n/α —
SIMULTANEOUS q/F_s AND n_{zp}/F_s
EQUIVALENT SYSTEM MATCH



* $1/T_{\theta_2}$ Free
\+ Freq. Range .3-10 rad/sec
B 1, 2 . . . Configuration No.

FIGURE D.1.12 ω_{sp} vs n/α —
SIMULTANEOUS q/F_s AND n_{cg}/F_s
EQUIVALENT SYSTEM MATCH

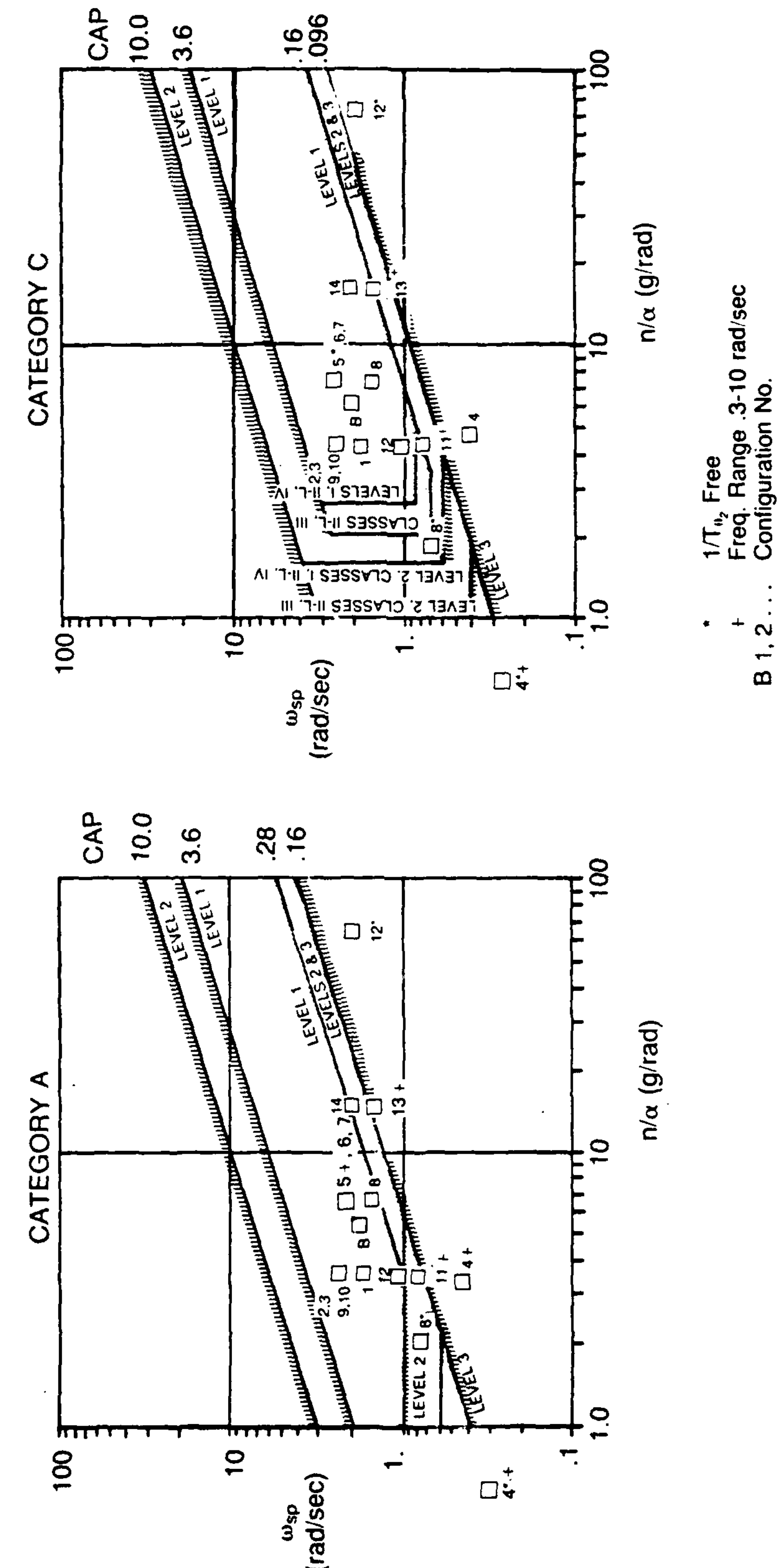
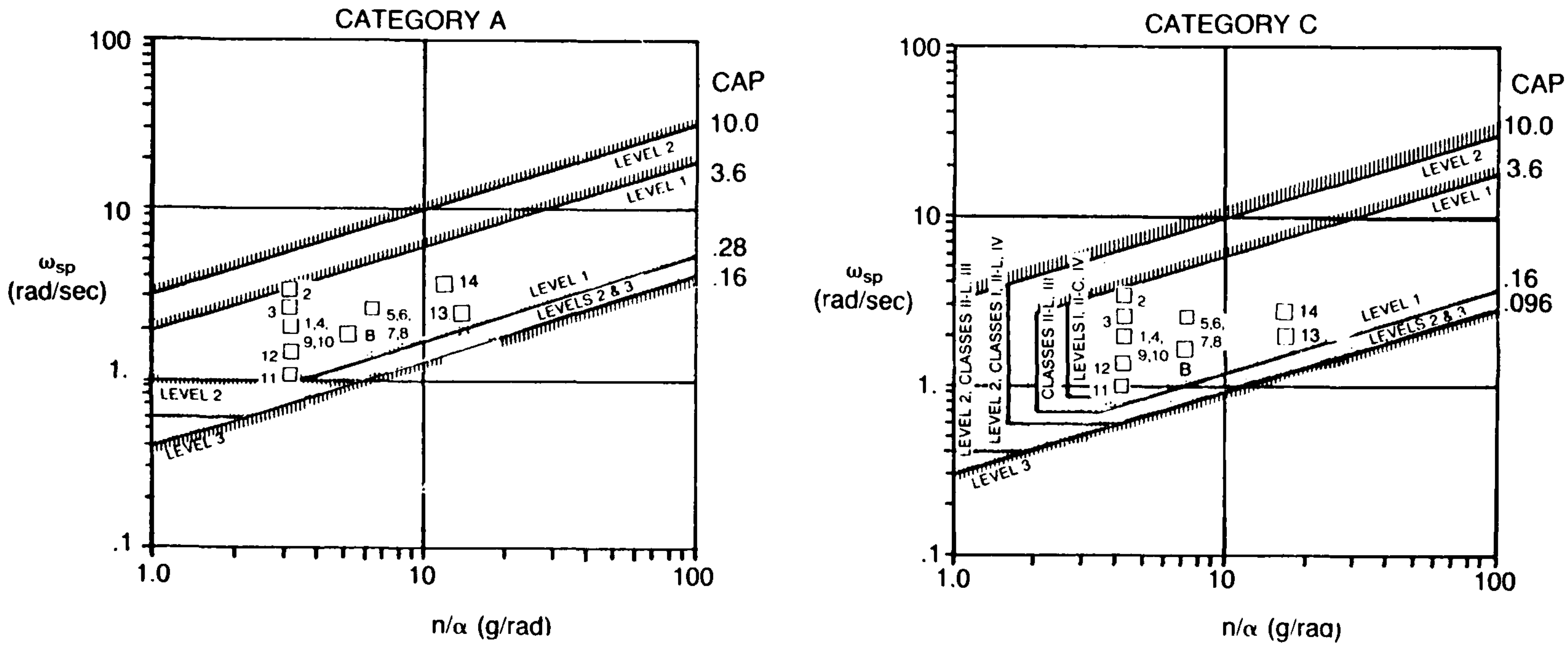
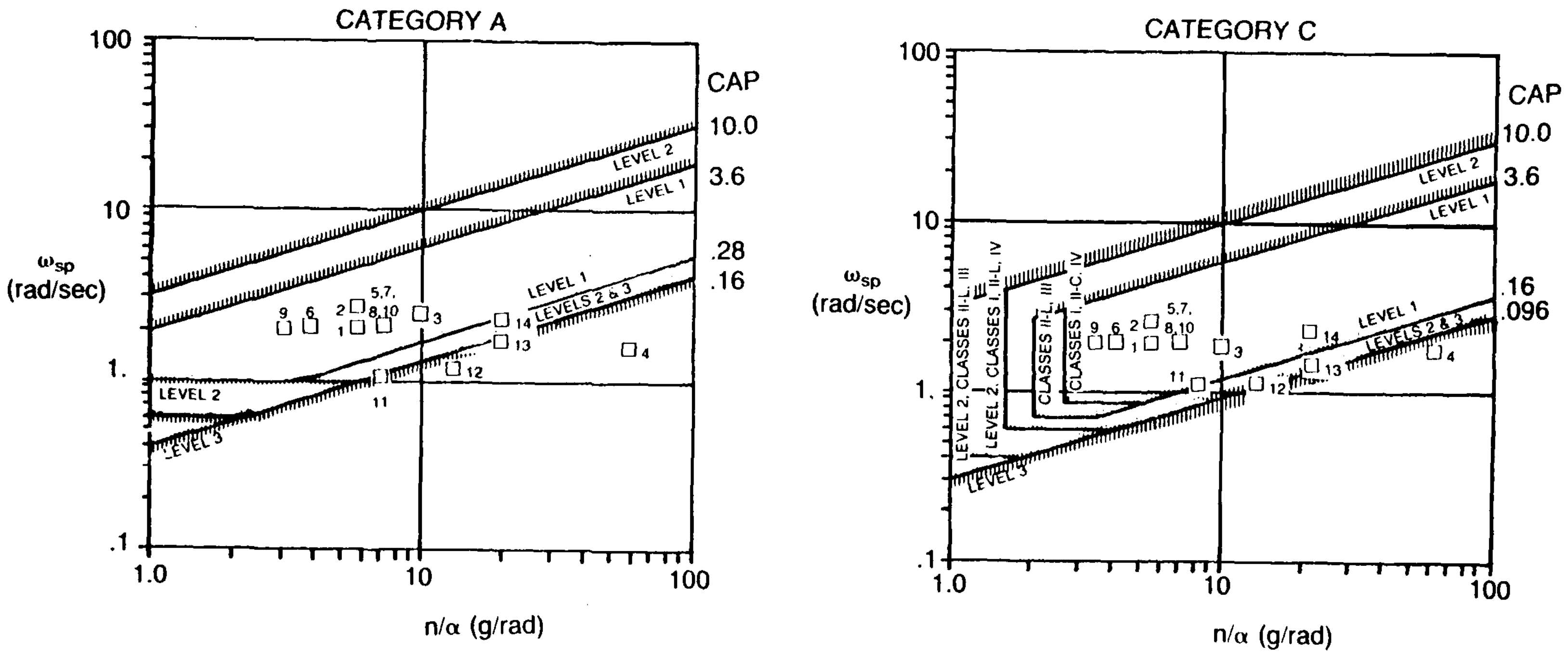


FIGURE D.1.13 ω_{sp} vs n/α — q/F_s EQUIVALENT SYSTEM MATCH



•	$1/T_{\theta_2}$ Free
+	Freq. Range .3-10 rad/sec
B 1, 2 . . .	Configuration No.

FIGURE D.1.14 ω_{sp} vs n/α —
α/F_s EQUIVALENT SYSTEM MATCH



• $1/T_{\theta_2}$ Free
ł Freq. Range .3-10 rad/sec
B 1, 2 . . . Configuration No.

FIGURE D.1.15 ω_{sp} VS n/α — TWO PART α/F_s THEN q/F_s EQUIVALENT SYSTEM MATCH

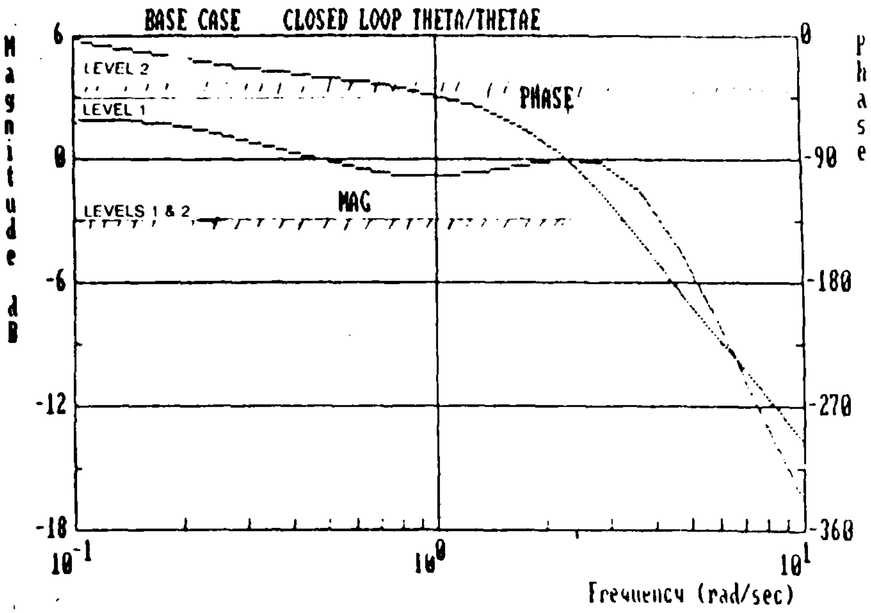


FIGURE D.2.1 CLOSED LOOP θ/θ_c BODE PLOT — BASE CONFIGURATION

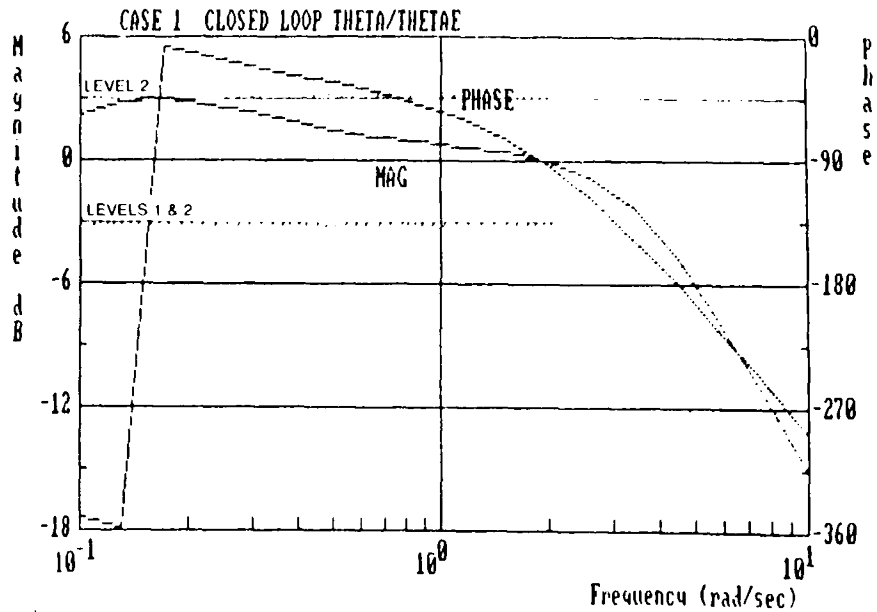


FIGURE D.2.2 CLOSED LOOP θ/θ_c BODE PLOT — CONFIGURATION I

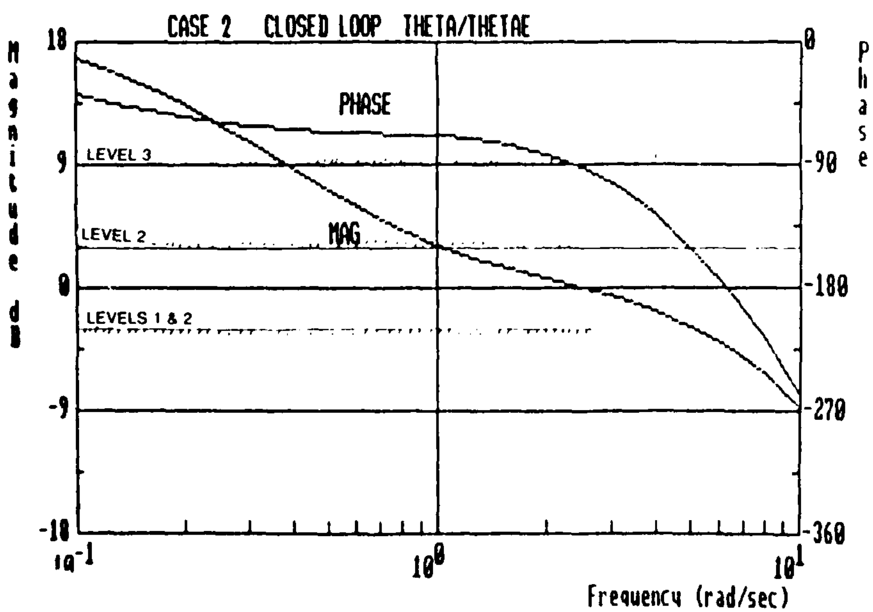


FIGURE D.2.3 CLOSED LOOP θ/θ_c BODE PLOT — CONFIGURATION 2

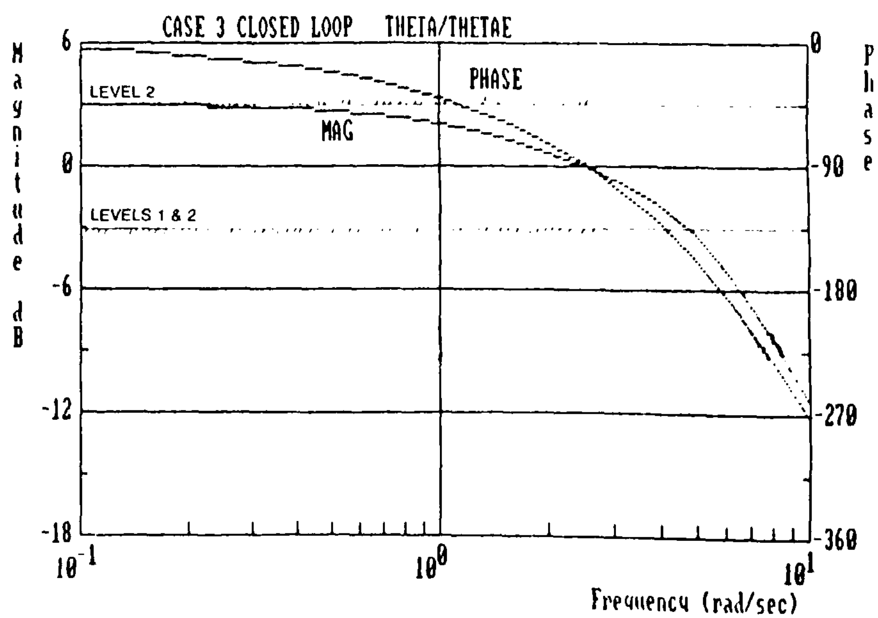


FIGURE D.2.4 CLOSED LOOP θ/θ_c BODE PLOT — CONFIGURATION 3

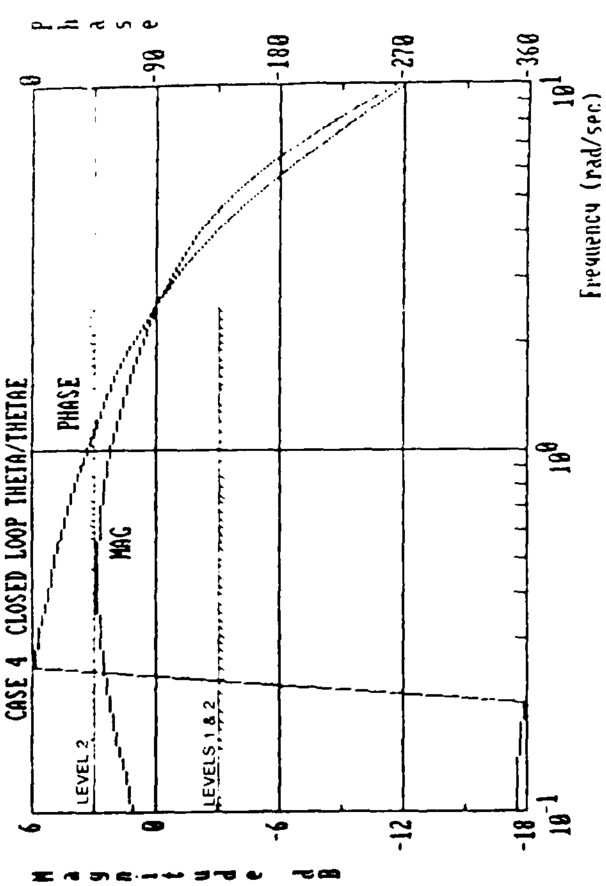


FIGURE D.2.5 CLOSED LOOP θ/θ_c BODE PLOT — CONFIGURATION 4

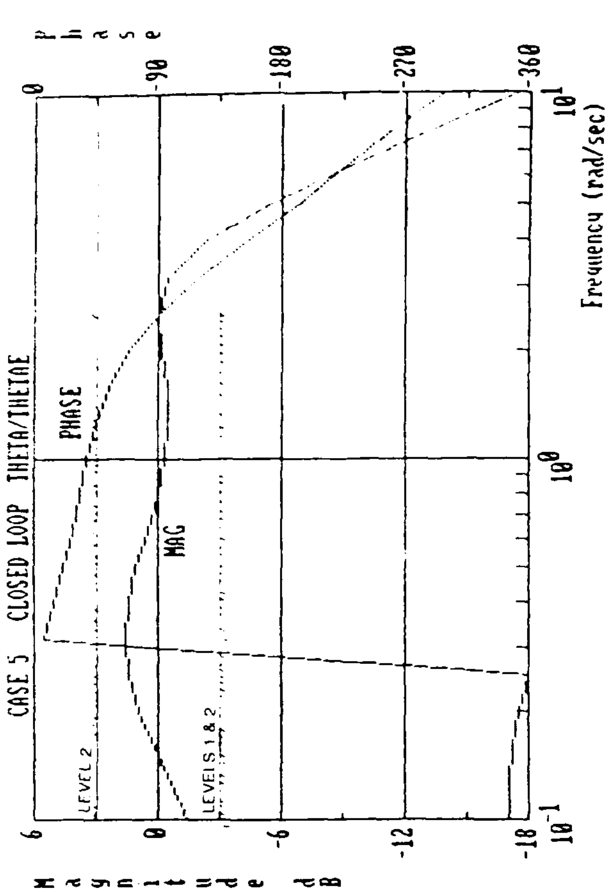


FIGURE D.2.6 CLOSED LOOP θ/θ_c BODE PLOT — CONFIGURATION 5

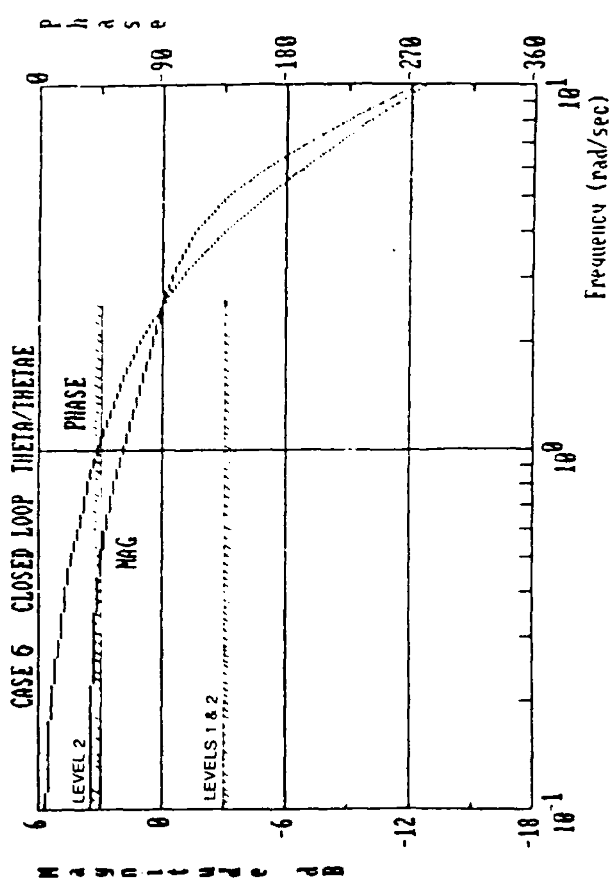


FIGURE D.2.7 CLOSED LOOP θ/θ_c BODE PLOT — CONFIGURATION 6

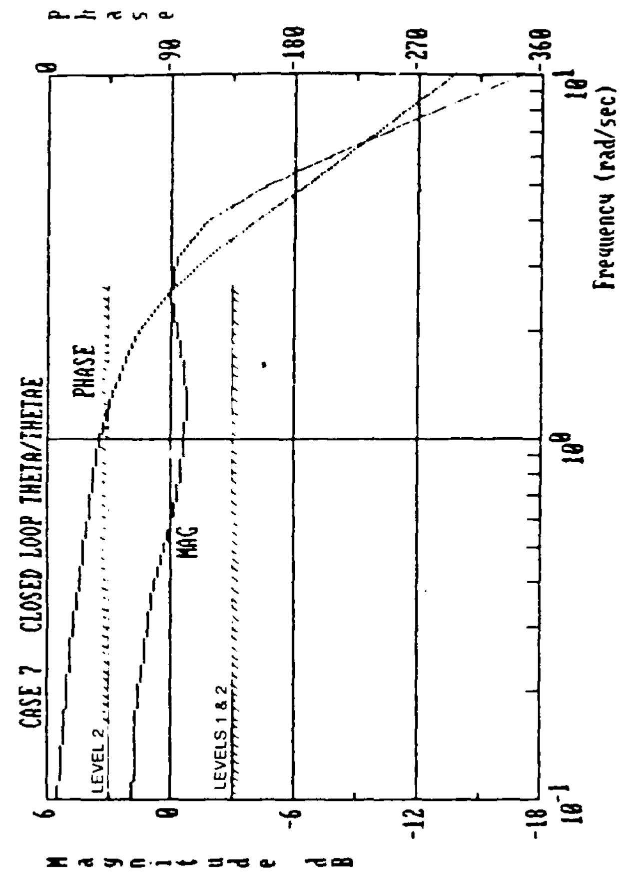


FIGURE D.2.8 CLOSED LOOP θ/θ_c BODE PLOT — CONFIGURATION 7

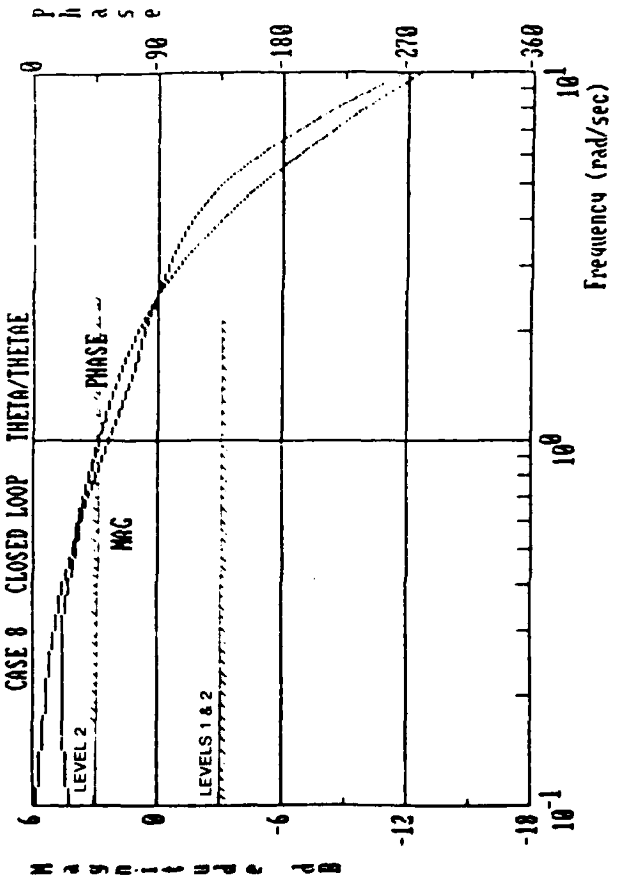


FIGURE D.2.9 CLOSED LOOP θ/θ_c BODE PLOT — CONFIGURATION 8

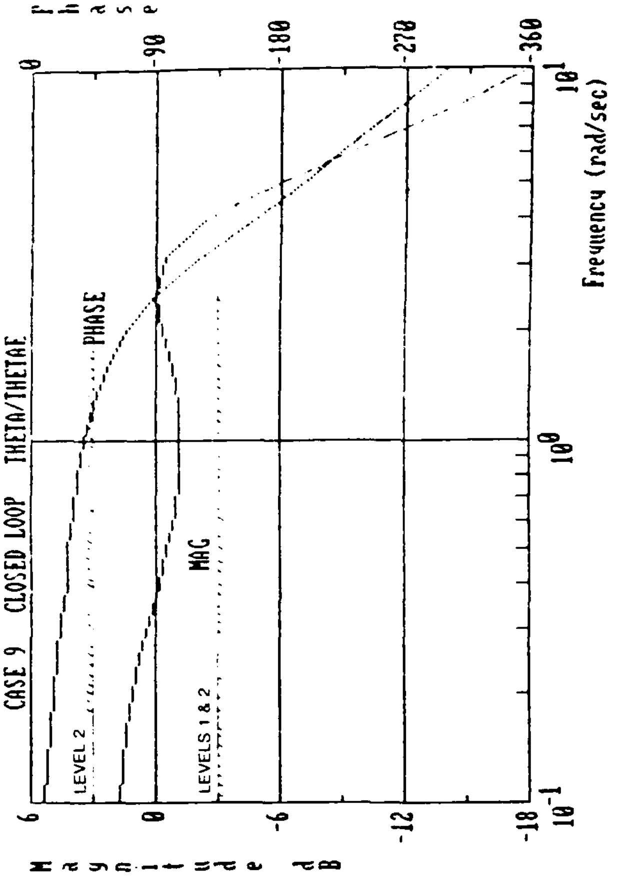


FIGURE D.2.10 CLOSED LOOP θ/θ_c BODE PLOT — CONFIGURATION 9

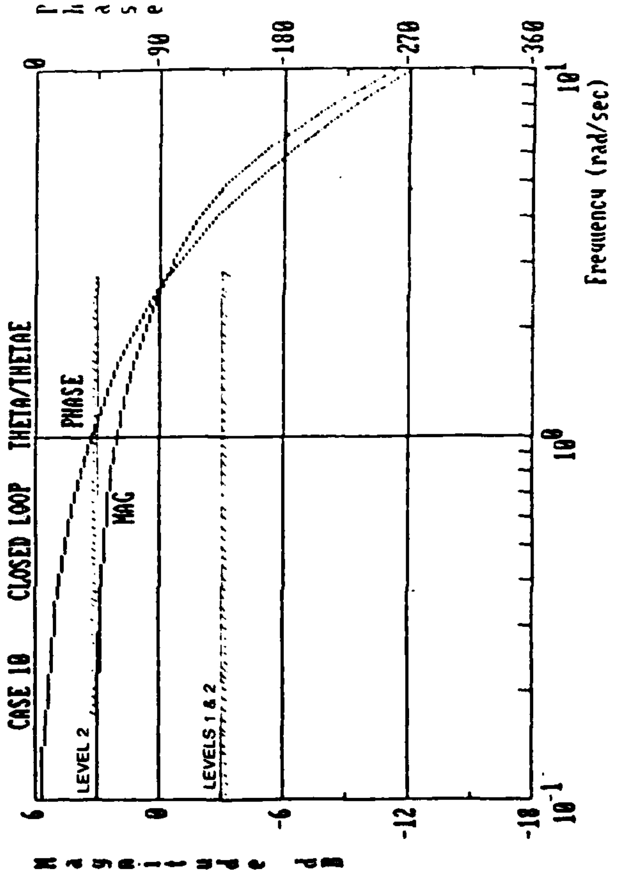


FIGURE D.2.11 CLOSED LOOP θ/θ_c BODE PLOT — CONFIGURATION 10

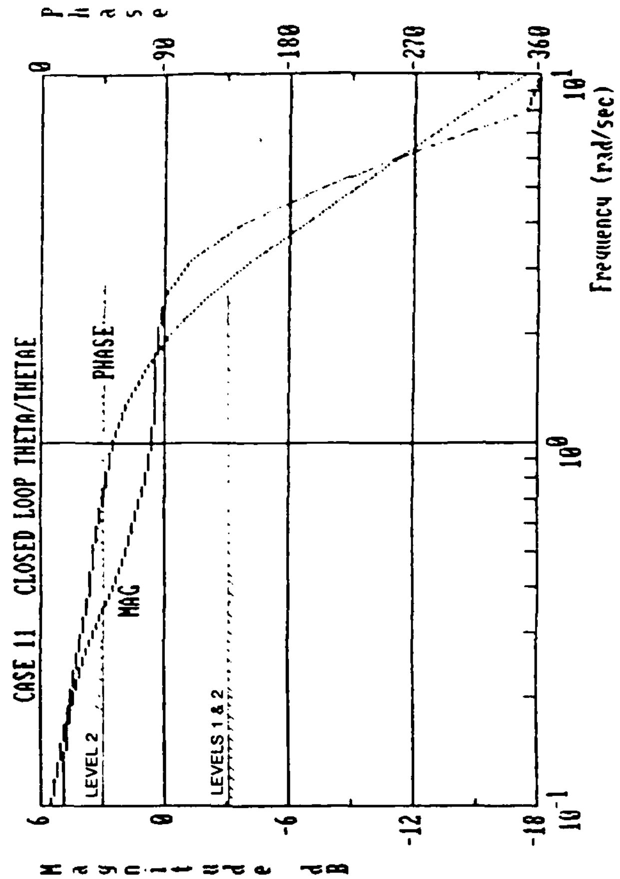


FIGURE D.2.12 CLOSED LOOP θ/θ_c BODE PLOT — CONFIGURATION 11

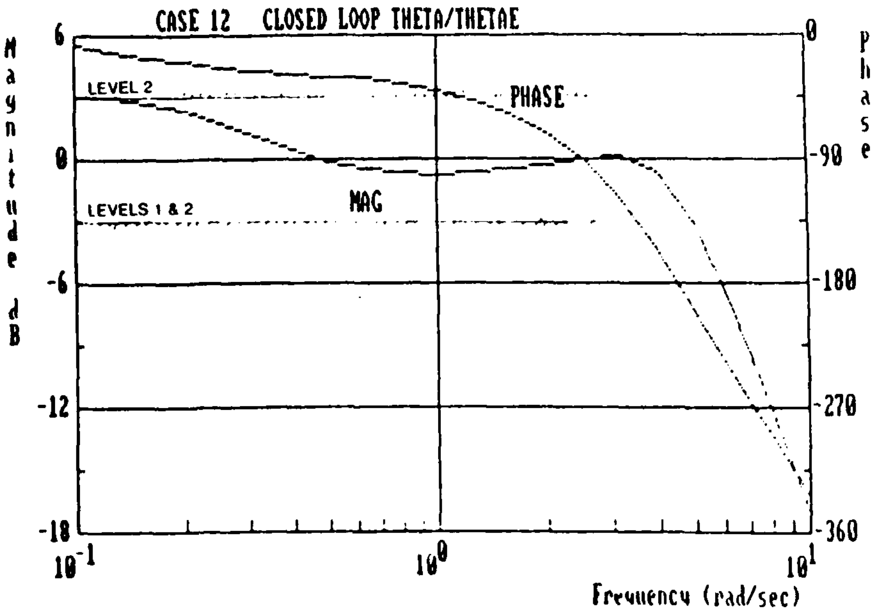


FIGURE D.2.13 CLOSED LOOP θ/θ_c BODE PLOT — CONFIGURATION 12

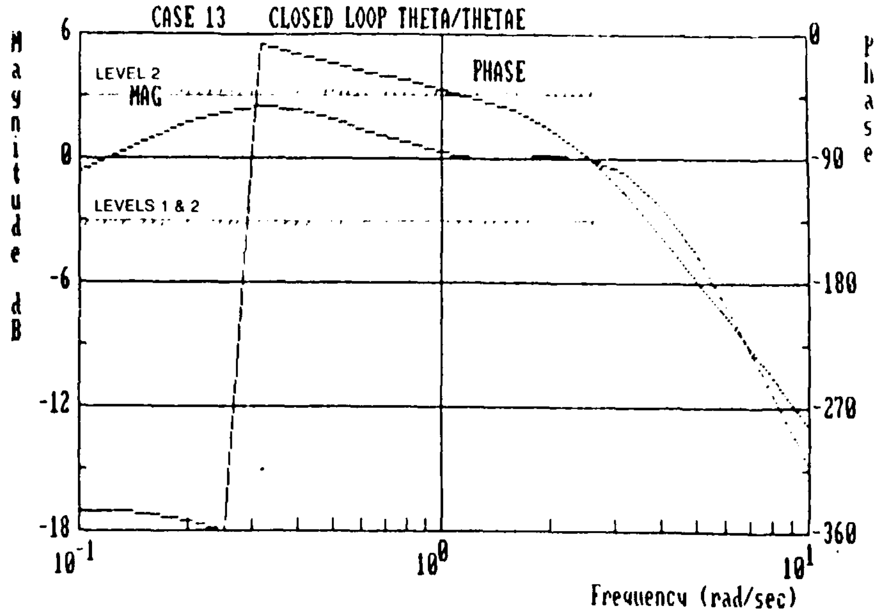


FIGURE D.2.14 CLOSED LOOP θ/θ_c BODE PLOT — CONFIGURATION 13

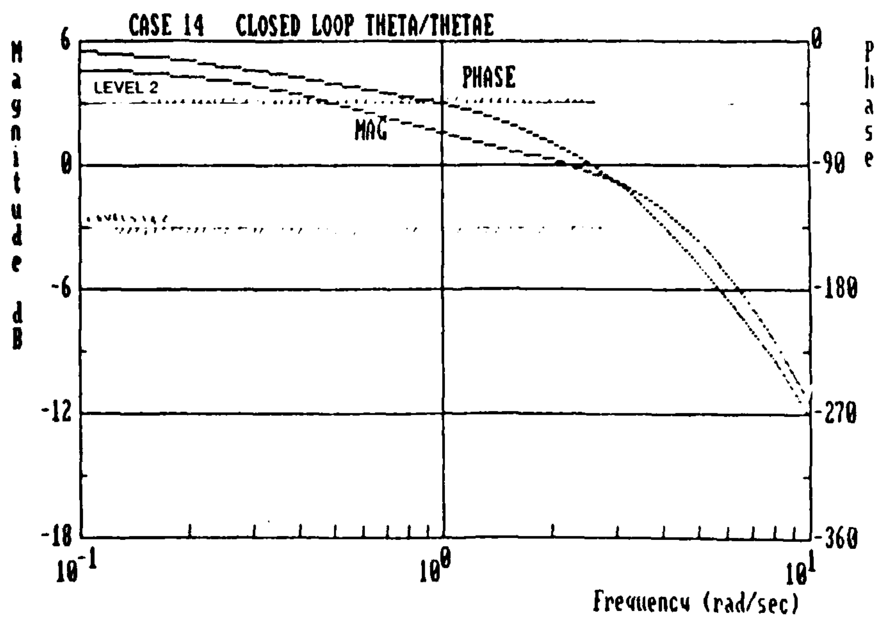


FIGURE D.2.15 CLOSED LOOP θ/θ_c BODE PLOT — CONFIGURATION 14

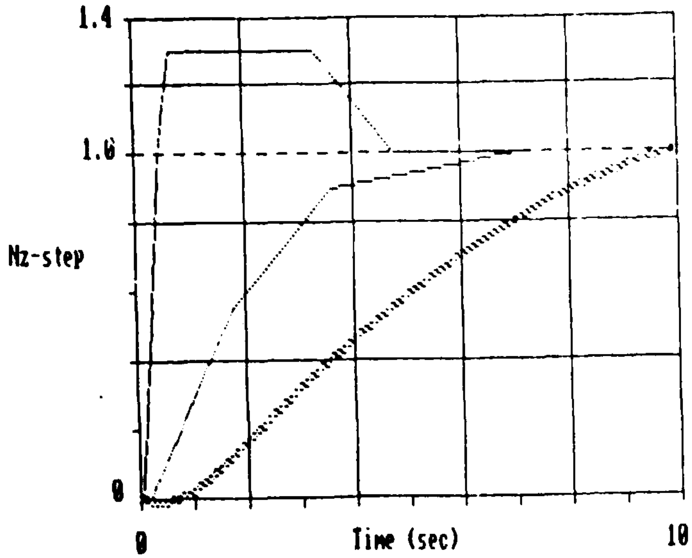


FIGURE D.3.1 NORMALIZED N_z RESPONSE — BASE CONFIGURATION

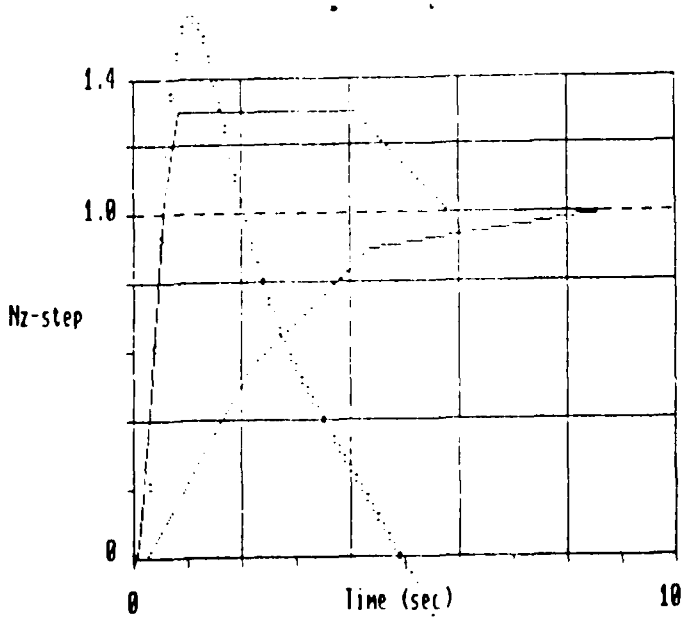


FIGURE D.3.2 NORMALIZED N_z RESPONSE — CONFIGURATION 1

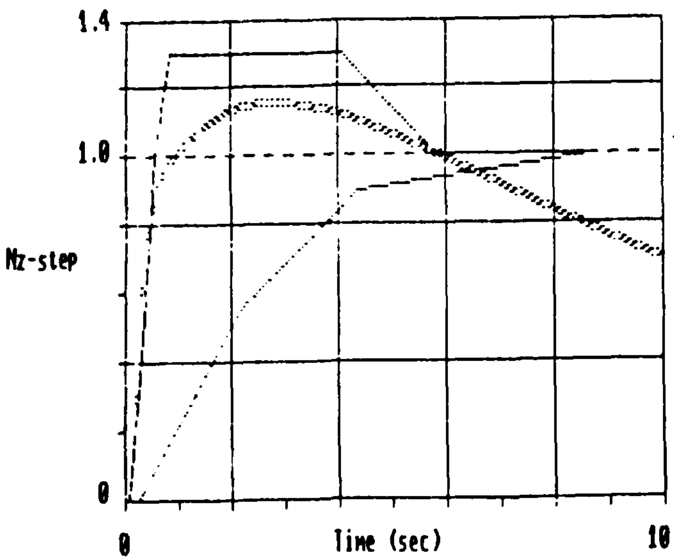


FIGURE D.3.3 NORMALIZED N_z RESPONSE — CONFIGURATION 2

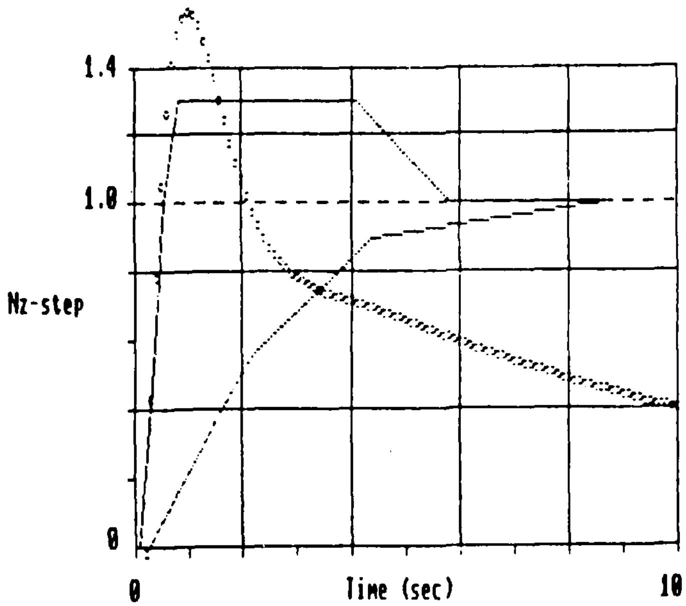


FIGURE D.3.4 NORMALIZED N_z RESPONSE — CONFIGURATION 3

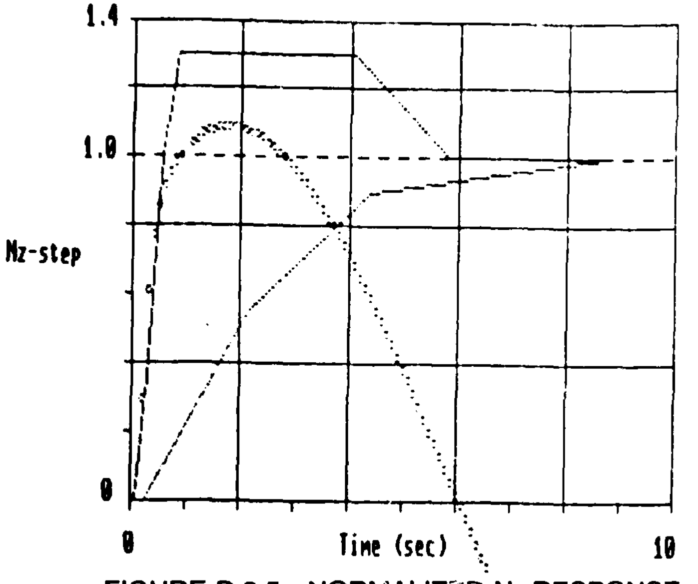


FIGURE D.3.5 NORMALIZED N_z RESPONSE — CONFIGURATION 4

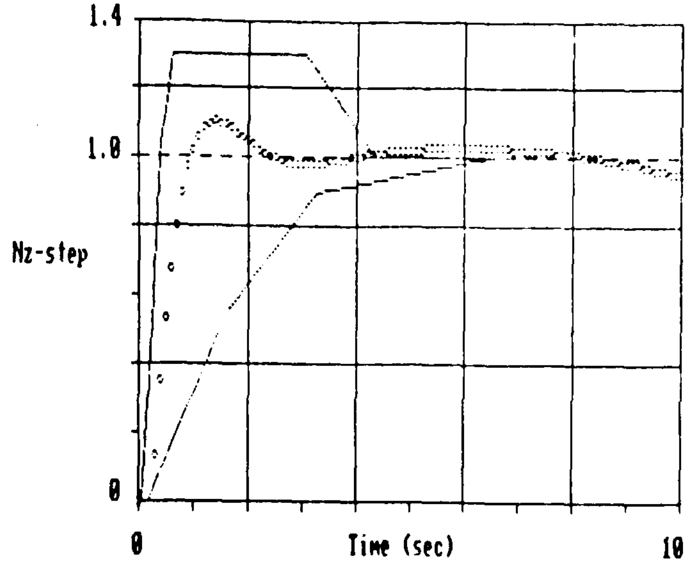


FIGURE D.3.6 NORMALIZED N_z RESPONSE — CONFIGURATION 5

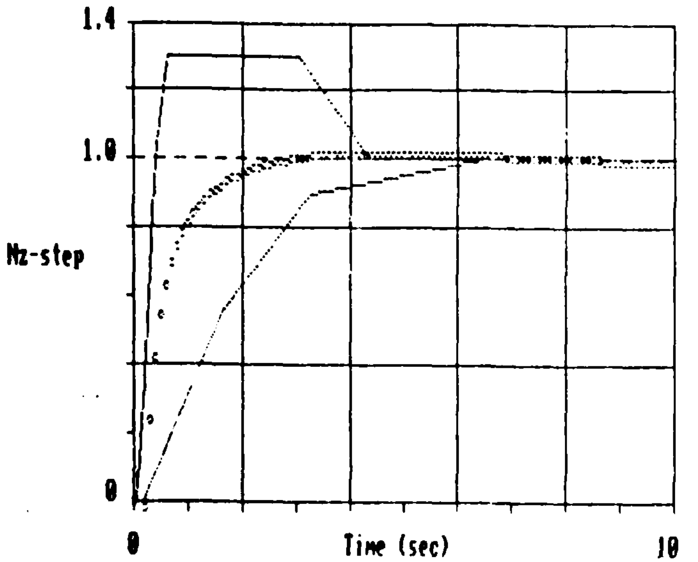


FIGURE D.3.7 NORMALIZED N_z RESPONSE — CONFIGURATION 6

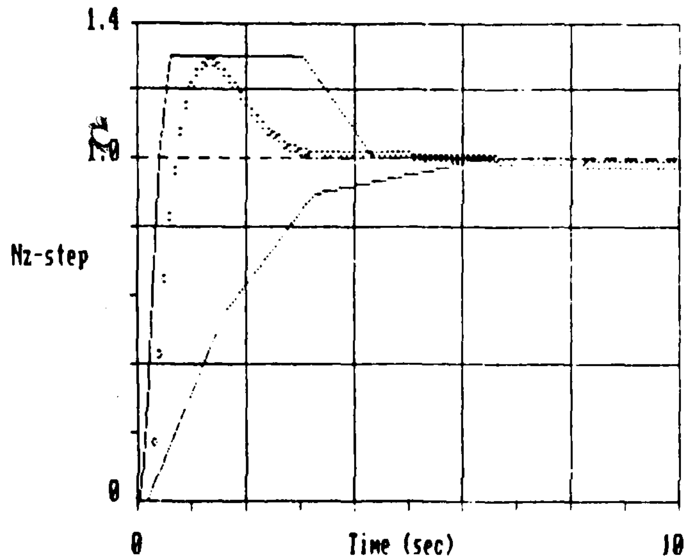


FIGURE D.3.8 NORMALIZED N_z RESPONSE — CONFIGURATION 7

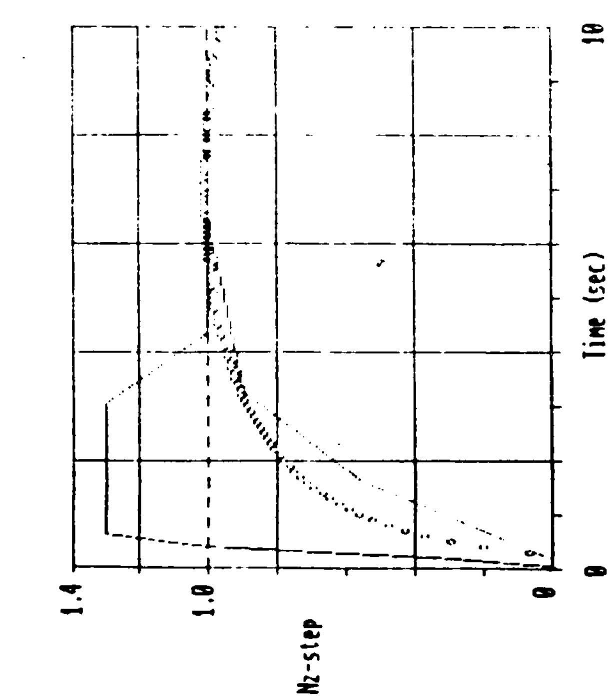


FIGURE D.3.9 NORMALIZED N_z RESPONSE — CONFIGURATION 8

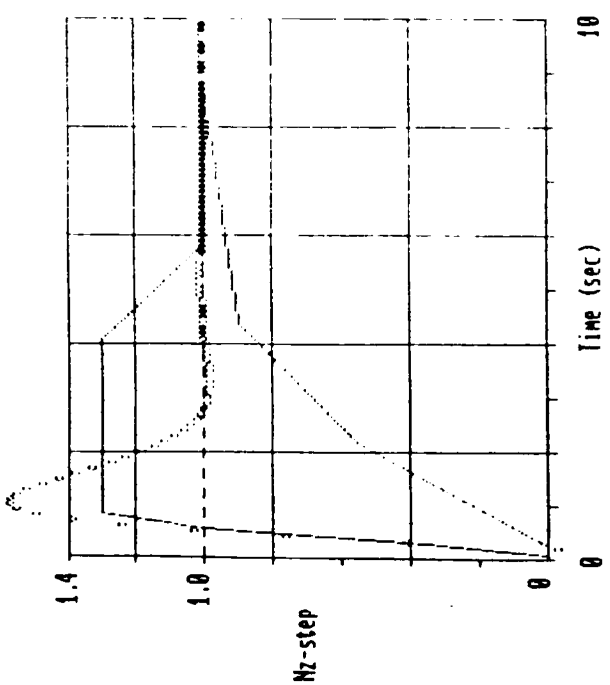


FIGURE D.3.10 NORMALIZED N_z RESPONSE — CONFIGURATION 9

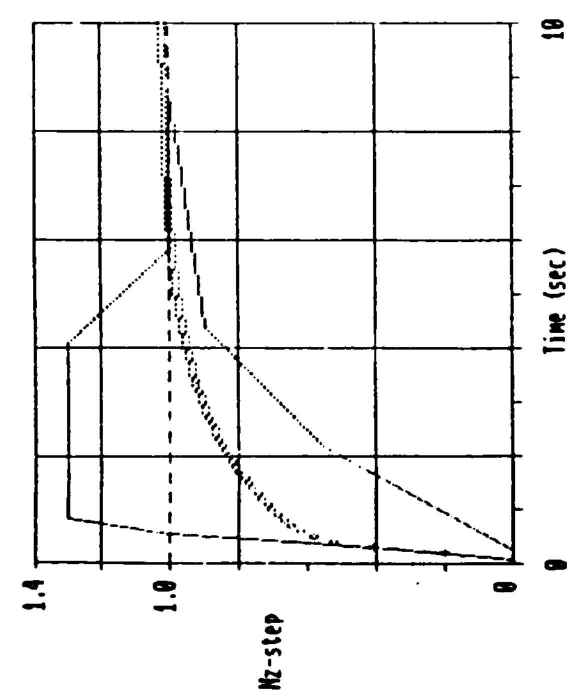


FIGURE D.3.11 NORMALIZED N_z RESPONSE — CONFIGURATION 10

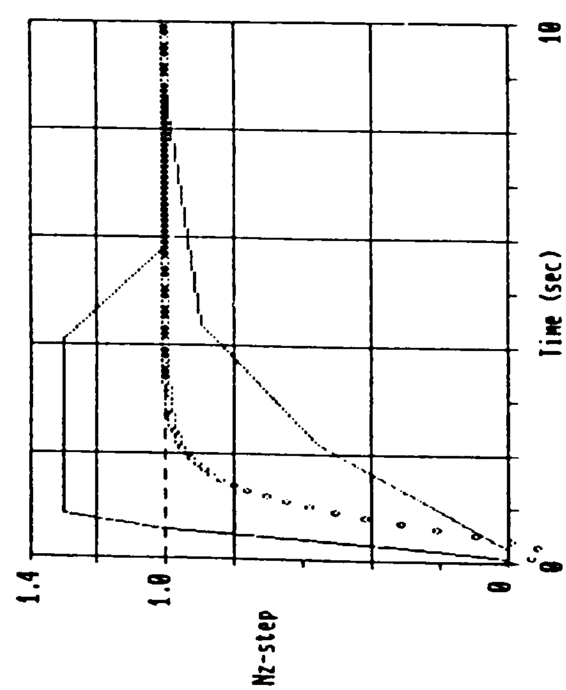


FIGURE D.3.12 NORMALIZED N_z RESPONSE — CONFIGURATION 11

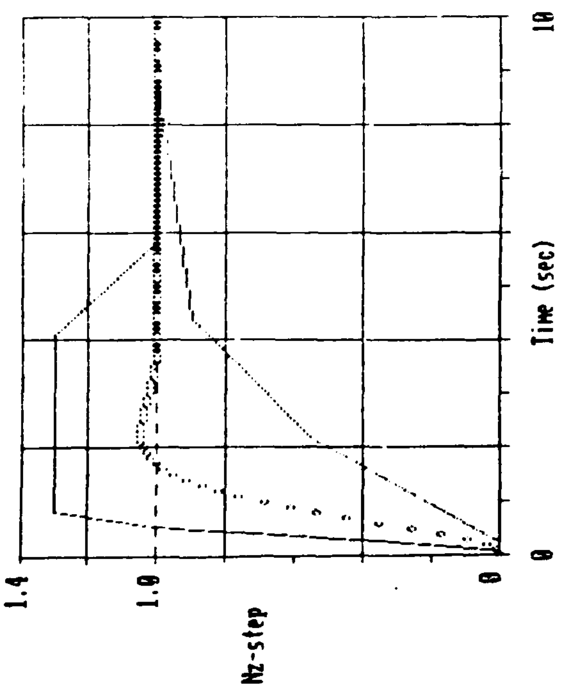


FIGURE D.3.13 NORMALIZED N_z RESPONSE — CONFIGURATION 12

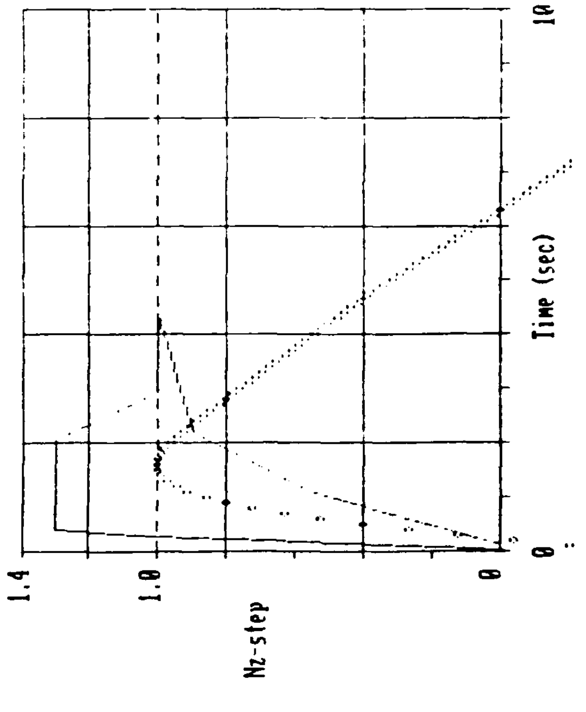


FIGURE D.3.14 NORMALIZED N_z RESPONSE — CONFIGURATION 13

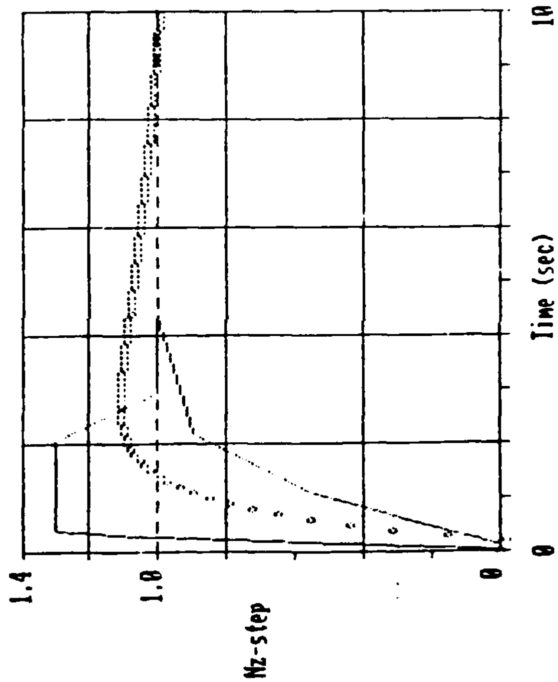


FIGURE D.3.15 NORMALIZED N_z RESPONSE — CONFIGURATION 14

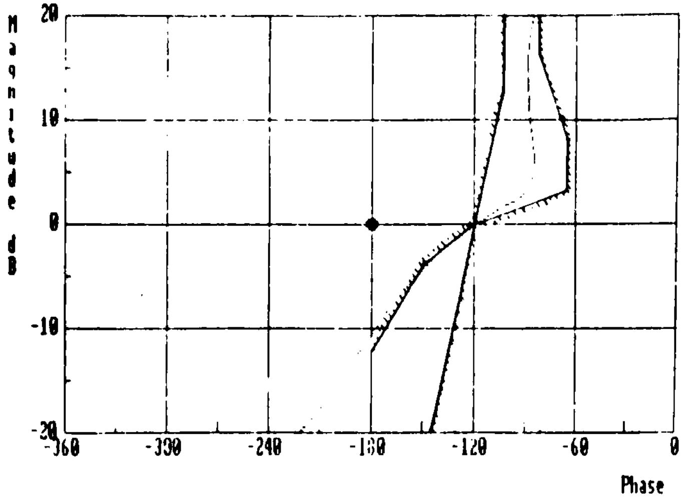


FIGURE D.4.1 OPTIMUM ATTITUDE BOUNDARIES — BASE CONFIGURATION $K \cdot |\theta/F_s|$

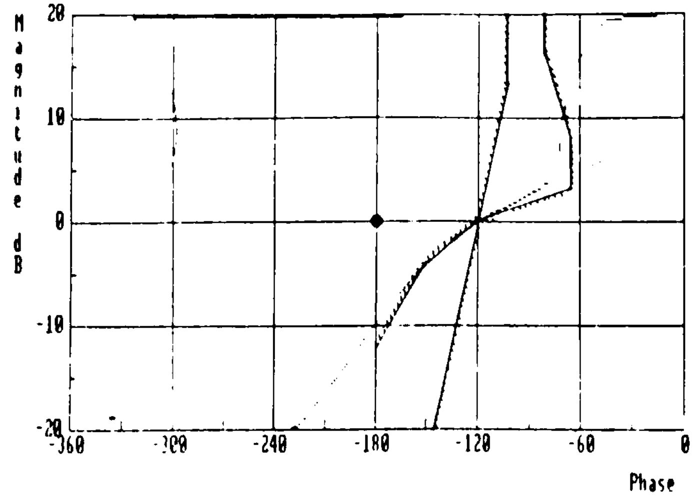


FIGURE D.4.2 OPTIMUM ATTITUDE BOUNDARIES — CONFIGURATION 1 $K \cdot |\theta/F_s|$

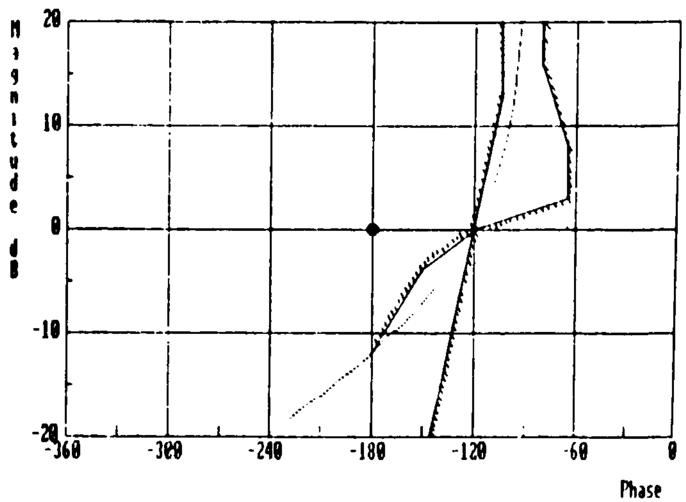


FIGURE D.4.3 OPTIMUM ATTITUDE BOUNDARIES — CONFIGURATION 2 $K \cdot |\theta/F_s|$

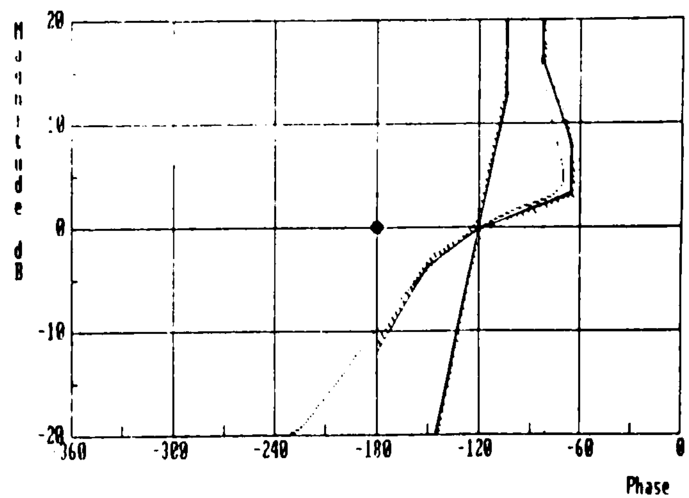


FIGURE D.4.4 OPTIMUM ATTITUDE BOUNDARIES — CONFIGURATION 3 $K \cdot |\theta/F_s|$

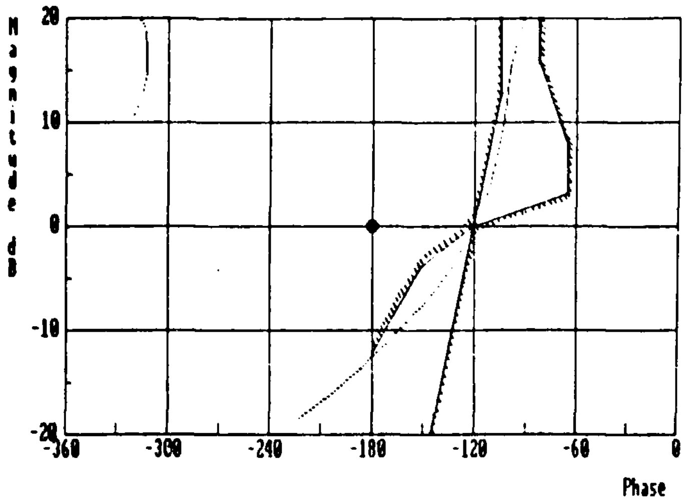


FIGURE D.4.5 OPTIMUM ATTITUDE BOUNDARIES — CONFIGURATION 4 $K \cdot |\theta/F_s|$

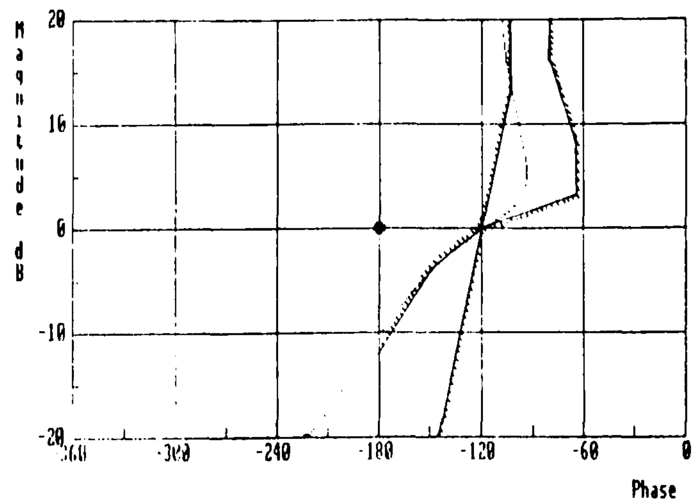


FIGURE D.4.6 OPTIMUM ATTITUDE BOUNDARIES — CONFIGURATION 5 $K \cdot |\theta/F_s|$

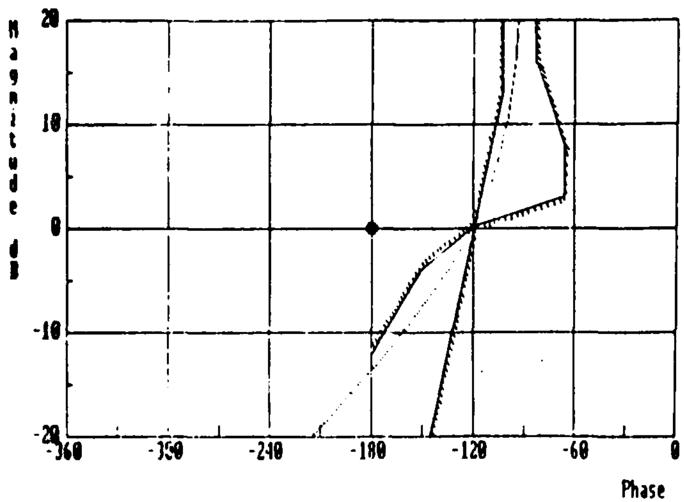


FIGURE D.4.7 OPTIMUM ATTITUDE BOUNDARIES — CONFIGURATION 6 $K \cdot |\theta/F_s|$

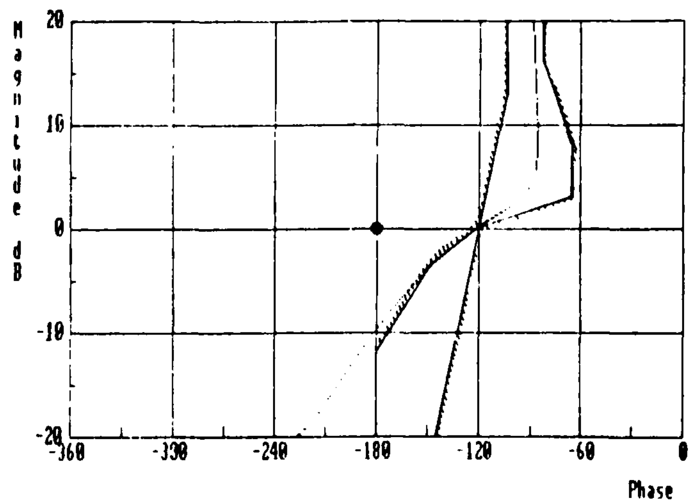


FIGURE D.4.8 OPTIMUM ATTITUDE BOUNDARIES — CONFIGURATION 7 $K \cdot |\theta/F_s|$

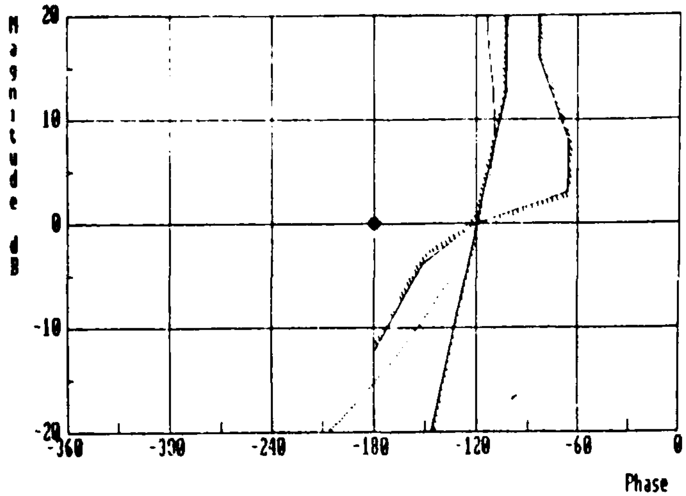


FIGURE D.4.9 OPTIMUM ATTITUDE BOUNDARIES — CONFIGURATION 8 K •|θ/F$_s$|

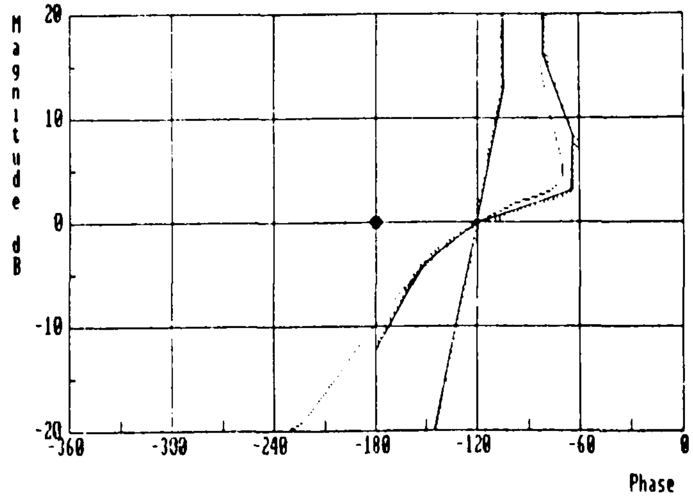


FIGURE D.4.10 OPTIMUM ATTITUDE BOUNDARIES — CONFIGURATION 9 K •|θ/F$_s$|

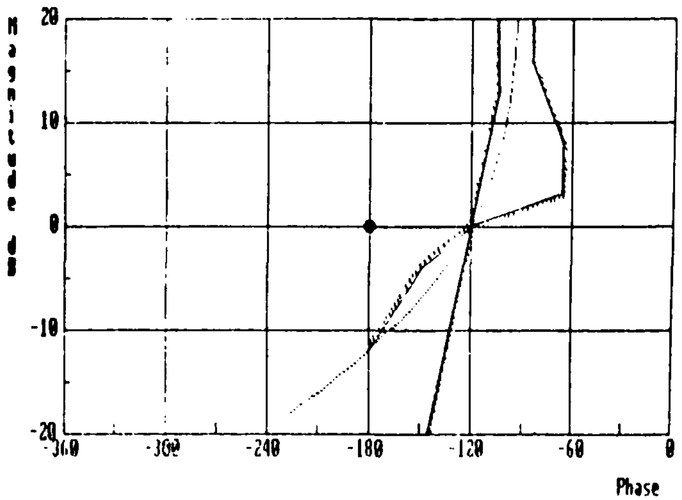


FIGURE D.4.11 OPTIMUM ATTITUDE BOUNDARIES — CONFIGURATION 10 K •|θ/F$_s$|

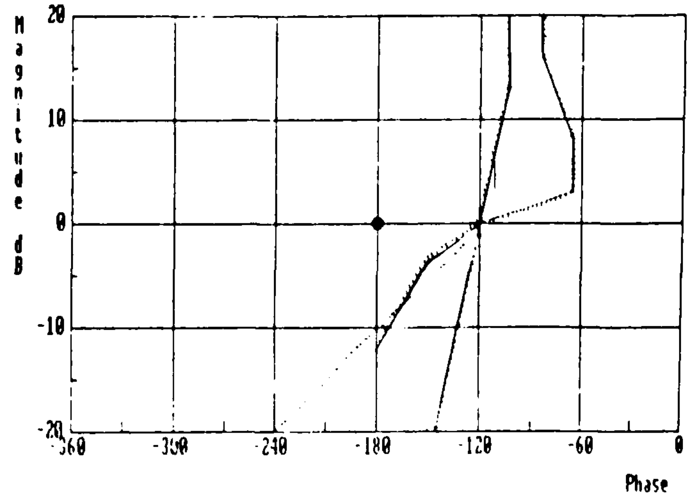


FIGURE D.4.12 OPTIMUM ATTITUDE BOUNDARIES — CONFIGURATION 11 K •|θ/F$_s$|

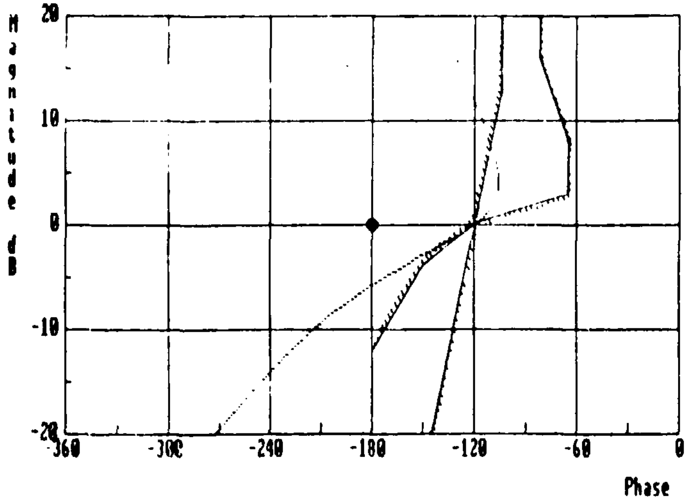


FIGURE D.4.13 OPTIMUM ATTITUDE BOUNDARIES — CONFIGURATION 12 $K \cdot |\theta/F_s|$

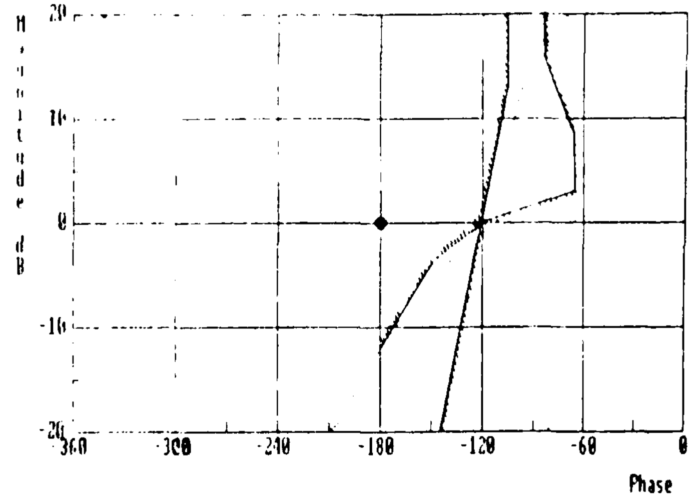


FIGURE D.4.14 OPTIMUM ATTITUDE BOUNDARIES — CONFIGURATION 13 $K \cdot |\theta/F_s|$

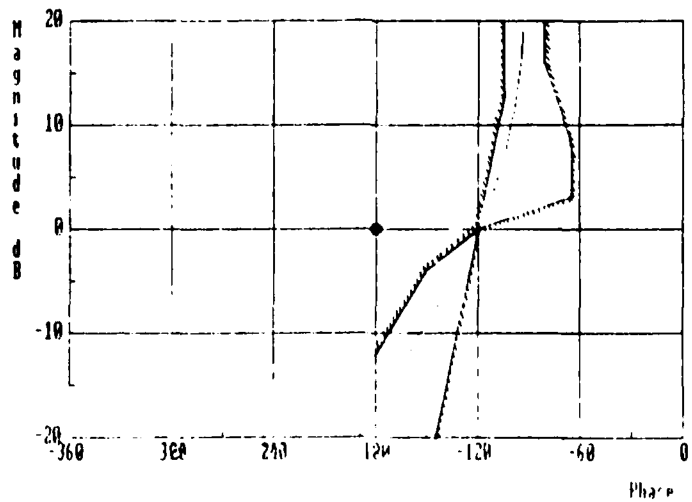


FIGURE D.4.15 OPTIMUM ATTITUDE BOUNDARIES — CONFIGURATION 14 $K \cdot |\theta/F_s|$

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